Drainage Index in Correlation of Agricultural Soils with Frost Action and Pavement Performance

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This paper deals with the application of selected concepts of pedology to highway soil-engineering problems. Particular emphasis is placed on the natural drainage index of a soil type as an indicator of its probable performance as a highway subgrade. The report is based on a study of representative soils of the glaciated portion of Wisconsin. Because of the severe climate, frost action in soils is a major consideration in the design of highways in this state.

The natural drainage index is primarily a function of the topographic position of the soil type and of the texture or textures of its profile. The soil association is a group of soils that commonly occur throughout a soil region. The individual soil types within this association may vary with respect to topographic position, texture, or both. Therefore each soil within this association has its particular drainage index. For agricultural purposes, these indices range from "excessively drained" to "very-poorly drained." The highway engineer probably will interpret these terms differently, but the drainage relationships of the soils are useful, nevertheless.

Soil samples were taken from selected horizons of 19 soil types. Each profile was assigned a generalized frost-susceptibility rating on the basis of the rating of each of its horizons. When these ratings are compared with the drainage index, it is shown that the soils that are least susceptible to frost action usually occupy the better drained positions, and the soils that are most susceptible to frost action are in the intermediate to poorly drained positions.

Another phase of the study was concerned with observations of pavement performance over several types of soil. On one study section, the actual amount of longitudinal and transverse cracking was determined for each of the several soil types traversed by the pavement. This pavement broke up the most where laid over poorly drained soils and performed better on the better-drained soils. On another study section, certain segments of the pavement had been resurfaced. When these segments are plotted on the soil map, it is shown that resurfacing was not generally required over the well-drained soils, that resurfacing alone was required over the intermediate soils, and that resurfacing plus a new base was required over the poorly-drained soils.

The results of this investigation indicate that the drainage index of the soil type may be of considerable value in soil engineering. This is borne out by the correlations with accepted soil classification systems and with the actual performance of soils as a subgrade.

● THE use of the pedological system of soil classification has attracted considerable interest, with several states using it to a greater or lesser extent in their soil engineering problems. Evidence of this interest is demonstrated by the series of bulletins published by the Highway Research Board dealing with the use of soil maps, aerial photos, and other means for determining soil conditions (6, 11, 12, 15). Some states have published detailed manuals as an aid to the interpretation of the significance of the various soil series and types (13).

This paper reports some of the results of a research project, the object of which was to develop general relationships between the pedological classification and recognized engineering classification systems. The project was divided into two major phases. The first phase consisted of determining the engineering classification of 65 samples taken from 19 selected soil profiles. The second phase consisted of observing the actual performance of pavements constructed over each of several soil series.

A number of significant relationships were developed or reaffirmed, but the most-important relationships appear to be those between the natural drainage index of the soil series and the Highway Research Board (now American Association of State Highway Officials) classification (1), the Corps of Engineers frost-susceptibility rating (10), and the actual performance of the pavements. The natural drainage index is a general expression of the natural soil moisture content and is a function of both the topographic position and slope of the soil body and of the texture of the soil profile.

Other relationships that appear to br significant include those between the textural classification and the susceptibility to frost action, and to pumping action under a rigid slab.

DRAINAGE INDEX ILLUSTRATED BY LANDSCAPE DIAGRAMS

The natural drainage index has been described as a measure of the natural moisture condition of the soil profile. It is influenced by both the texture or relative permeability of the soil profile and the landscape position and slope, which governs both surface and subsurface drainage. There are, of course, many variations and combinations of these factors, but a few illustrations will serve to point out the possible range. For instance, a sand could be "excessively drained" if in a relatively high position, or "moderately well drained" if in a depression and if underlain by a less-permeable layer. A silt or till soil on a hill would be "well drained" or possibly better, but in lower lying positions, especially in depressions, the same texture would be "poorly drained."

It should be pointed out here that the engineer and the agronomist probably will not interpret these word descriptions in the same manner. While the highway engineer usually would think of a sand as being "excellently drained," the agronomist would consider this same material to be "excessively drained." Many silt loam soils would be rated as "well-drained" by the agronomist, but the engineer would probably consider the drainage only "fair." Recognizing the difference in interpretation, this report will use the soil mapping terminology, rather than the terminology that might be suggested by engineering considerations.

With the objective of condensing and clarifying the many items that enter into a complete pedologic description of soil bodies, F. D. Hole has suggested certain terms, and corresponding numerical scales to permit the writing of the soil description in a numerical shorthand (7). One of the descriptive items for which he proposes a numerical index is the natural drainage of the soil.

In the system he proposes, well-drained soils are arbitrarily assigned the value of +1. An organic soil or bog soil is rated as +10, very-poorly drained, while a soil that is very-excessively drained is rated as -10. Soils of drainage characteristics between these extremes are assigned appropriate numbers to indicate their relative position in the sequenc This system will be further illustrated by a definite example.

If all the possible combinations of texture and topographic position that condition the drainage of the soil are considered, the range at first seems too great to comprehend and organize into workable units. However, the number of soil series in a given landscape association or major soil region is not large. By studying the relationships between the members of one association, a good idea of their probable nature can be developed. The soils belonging to an association are related because of similarities in climate and geological history and typically occur together in fairly consistent patterns. Furthermore, soil associations occur in rather well-defined zones or belts, which fact facilitates their study considerably. This is illustrated by Figure 1, a map of the major soil regions as recognized in Wisconsin at the time of the study.

Within a given association or soil region, the general nature of the various soil series can be shown rather well by means of landscape diagrams (14b). Figure 2 illustrates a fe of the important considerations. The Rodman soil, formed from gravel and sand, is "excessively drained" (natural drainage index of -10). The Bellefontaine soil is " somewhat excessively drained," -2. The difference in drainage, compared to the Rodman soil, is a

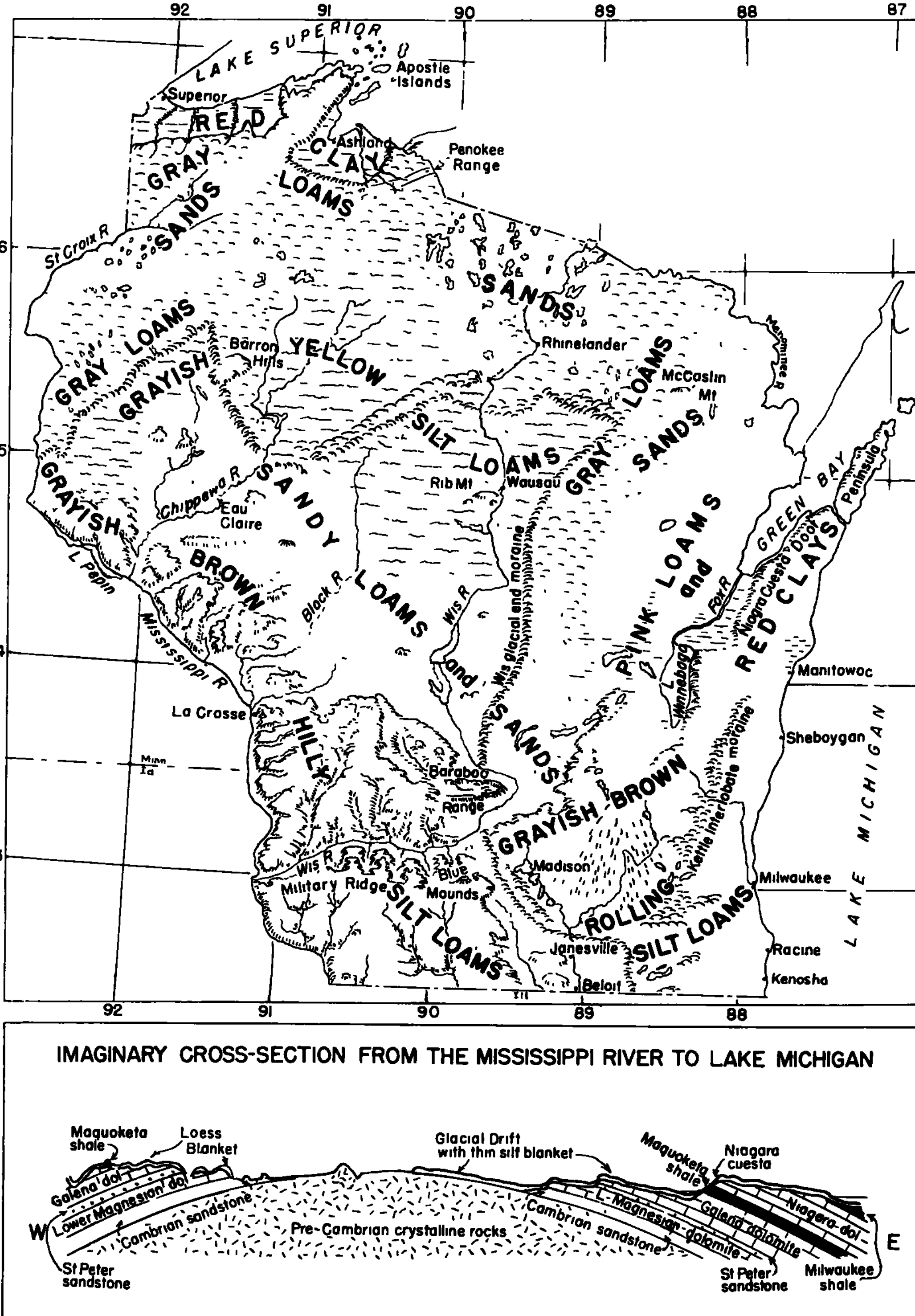


Figure 1. Major soil regions of Wisconsin. (The Soil Survey Division, Wisconsin Geological and Natural History Survey.)

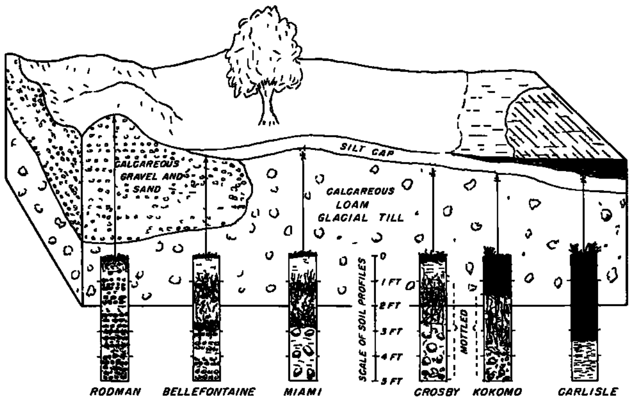


Figure 2. Typical soils of the grayish-brown rolling silt-loam region. (Soil Survey Division, Wisconsin Geological and Natural History Survey.)

result of its lower position, and to a minor extent, of the thin silt cap covering the gravel and sand. Although the Miami soil may be actually somewhat higher in the landscape than the Bellefontaine, it is rated as "well-drained," +1, because of the loam till underlayer, with a silt cap of moderate thickness.

The only difference between the Miami and the Crosby is the position, yet the Crosby soil is sufficiently lower to be rated as imperfectly drained, +4. The Kokomo soil is a marsh border soil, only slightly lower than the Crosby, but very-poorly drained, +8.5. The Carlisle soil is a bog soil, very-poorly drained, +10.

The gravel and sand are of glacial origin, as is the loam till. The silt cap is a wind-blown deposit that may be as thick as 4 feet.

Other diagrams have been prepared by Hole to illustrate other soil association areas (14c).

STUDY OF SELECTED SOIL PROFILES

As stated in the introduction, the objective of this phase was to determine the engineer ing classification of the significant horizons of several soil profiles and to see what general relationships or correlations could be determined, if any. Soil profiles were selected from a wide range of soil series and major soil regions in Wisconsin's glaciated area. These ranged from "excessively drained" soils to "very-poorly drained soils," to use the terminology of the soil surveyor.

The test program consisted of determining the liquid limit, the plasticity index, and the mechanical analysis. The results of these tests permitted the AASHO classification and the Corps of Engineers frost-susceptibility rating to be determined for each of the horizons studied.

The relationship between AASHO subgroup and the group index number is shown in Tab 1. This is of interest because tentative thicknesses of flexible pavement were suggested for given ranges of the group index number (1), and the Washington State Highway Department has tabulated thicknesses required for each subgroup (8). When actual soils are pro erly located in this table, it is possible to check the extent of agreement between the two systems.

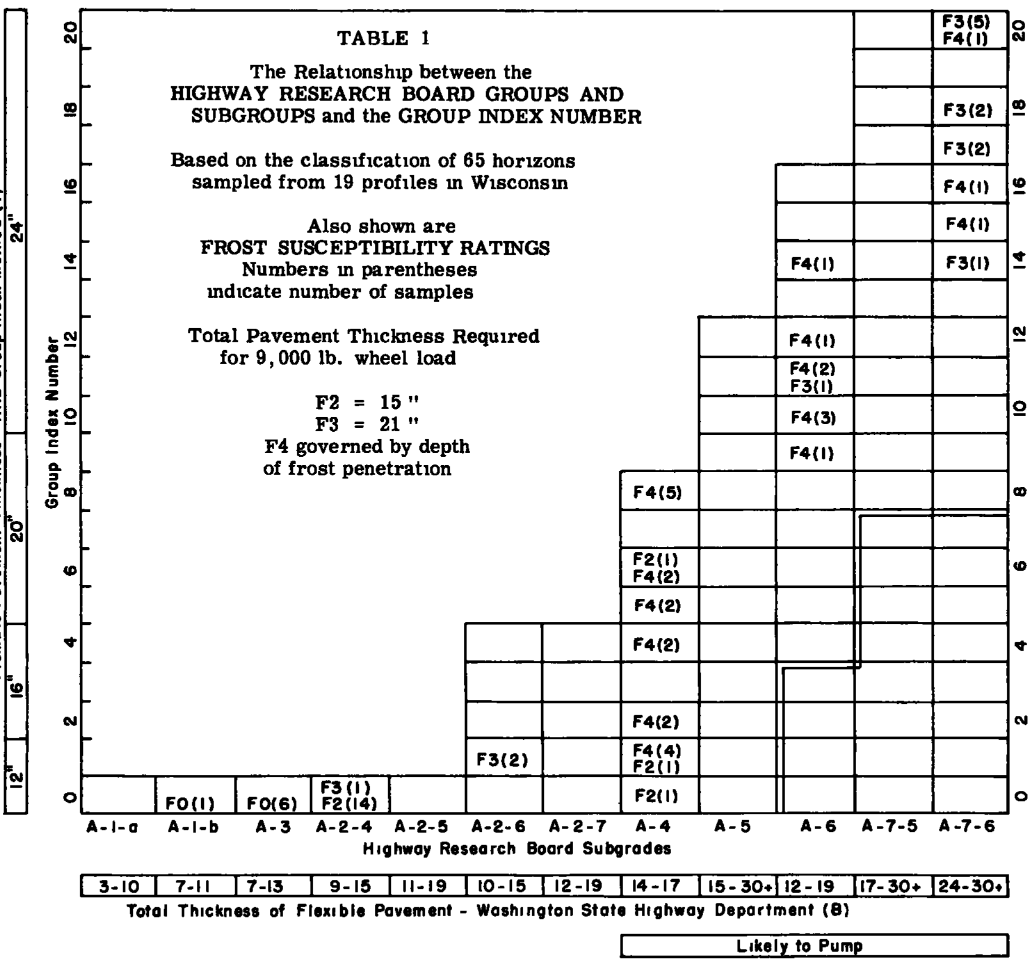
This table also shows the frost-susceptibility ratings of the soils tested, located in the table according to group and group index number. On the basis of this table, it may be concluded that there is no significant relationship between the group index number and the frost-susceptibility rating. There is a general correlation between frost action and the su groups, however. A-1 and A-3 soils probably are not susceptible to frost action, A-2 soi are moderately frost-susceptible, A-4 soils are moderately to very-highly frost susceptib and A-6 and A-7 soils are highly to very-highly frost susceptible. The differences in pave ment thickness required are due primarily to differences in the duration and magnitude of subfreezing temperatures.

The criteria for the frost-susceptibility ratings referred to in the preceding paragraph may be briefly summarized as follows: F-0, generally not frost-susceptible; F-1, gravelly soils containing between 3 and 20 percent finer than 0.02 millimeter by weight; F-2, snads containing between 3 and 15 percent finer than 0.02 millimeter by weight; F-3, (a) gravelly soils containing more than 20 percent finer than 0.02 millimeter by weight, and sands, except fine silty sands, containing more than 15 percent finer than 0.02 millimeter by weight and (b) clays with plasticity indices of more than 12, except varved clays; F-4, (a) all silts including sandy silts, (b) fine silty sands containing more than 15 percent finer than 0.02 millimeter by weight, (c) lean clays with plasticity indices of less than 12, (d) varved clays.

The rating F-0 is not included in the original system, but the author has taken the liberty of adopting that designation for soils not susceptible to frost action.

From the above criteria it can be seen that the relative frost susceptibility of soil is largely a function of its mechanical analysis or texture. This suggests plotting the several samples on the triangular textural chart and indicating the frost-susceptibility rating. Figure 3 is such a chart, based on the chart currently used by the agricultural soil survey agencies and the 2-micron definition of maximum-size clay particles.

The results of this correlation may not be surprising to those persons well acquainted with the nature of frost action. However, there are a few rather clear-cut patterns that



may be of interest. These patterns suggest the following conclusions: (1) It is emphasized again that the silts are the worst offenders with respect to frost action. (2) Within proper limitations, it appears that the frost-susceptibility rating could be determined from the textural classification with reasonable accuracy. (3) Clays, clay loams, silty clays, and silty clay loams are likely to have an F-3 rating. (4) Silts, silt loams, and loams are likely to have F-4 ratings. (5) Sands may range from F-0 to F-2. (6) All the loamy sands had an F-2 rating, but inspection of the pattern in the area of loamy sands and sandy loams near the line of zero clay indicates that there is a very narrow boundary between F-2 and F-4 ratings. This arises from the criteria used in establishing the frost susceptibility ratings originally. (7) Sandy loams are likely to be either F-3 or F-4, depending upon the precise amount of silt present. (8) To the extent that this sampling is representative of Wisconsin soils, most of them are frost-susceptible. Of the 65 samples analyzed, 7 rated F-0, 17 rated F-2, 15 rated F-3, and 26 rated F-4. (9) In the zones on the chart where slight differences are critical, an abbreviated mechanical analysis by

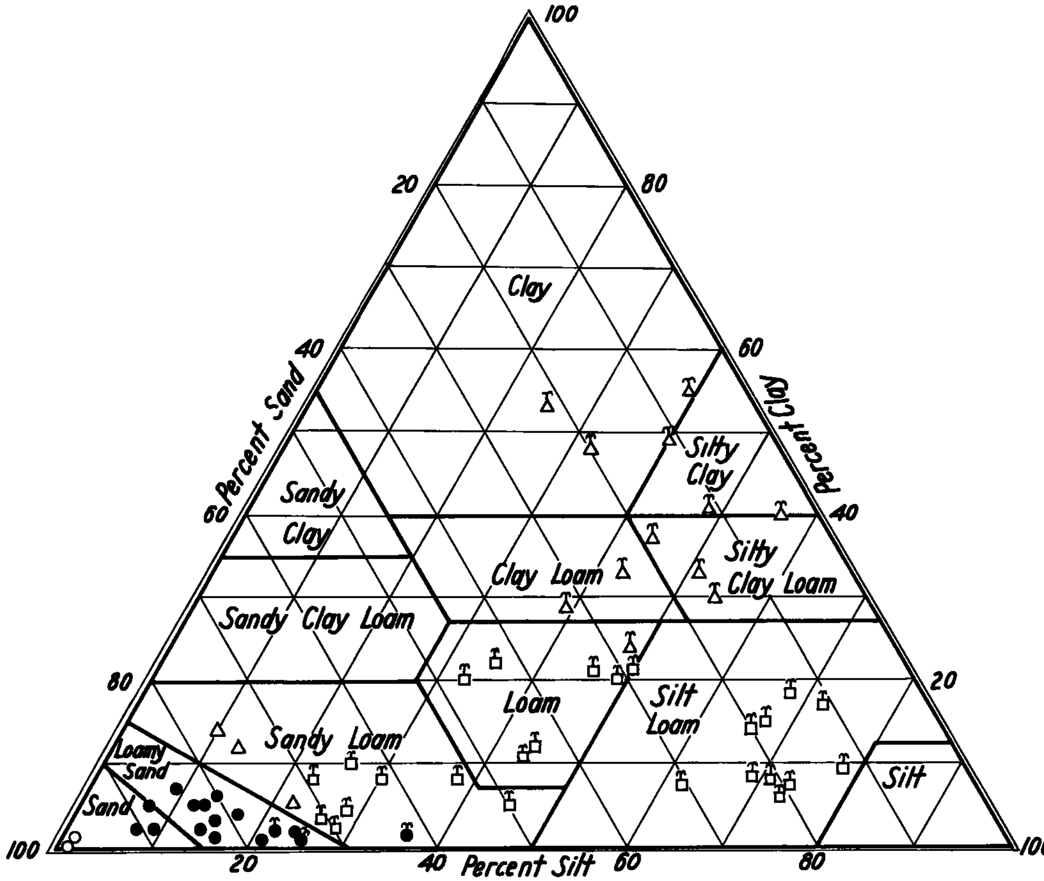


Figure 3. Relationship of frost-susceptibility rating and pumping to textural classification O = FO ● = F2 Δ = F3 □ = F4 τ added to any of above symbols indicates that the soil is susceptible to pumping action under rigid slabs.

by sedimentation methods (determining the percent finer than 0.02 millimeter) supplementing the textural classification would establish the correct frost-susceptibility rating.

The same figure indicates some possible correlations with susceptibility to pumping action under rigid slabe. These conclusions are as follows: (1) Clays, silty clays, silty clay loams, clay loams, silt loams, and loams are very likely to pump. (2) Sands are not likely to pump. (3) The correlation is not good for sandy loams and loamy sands, but it appears that about 20 percent silt is the maximum for a nonpumping soil. This would require further analysis to make a final determination. (4) With few exceptions, soils with frost-susceptibility ratings of F-3 and F-4 are also susceptible to pumping. (5) Soils that are rated F-2 generally are not susceptible to pumping, with a few exceptions where the silt content is rather high.

For the above correlations of pumping with the textural chart, the gradation of each sample was compared with criteria used in North Carolina (6), and in Ohio (12). In Ohio, it was discovered that pumping was confined principally to soils having more than 45 percent of the particles passing the No. 200 sieve. Pumping was also related to the frequency of loading of heavy axles.

North Carolina has established rather detailed specifications for "blotter" courses to be used under rigid pavements. These are provided specifically to prevent pumping action. The minimum specification for this material is as follows:

100 percent	passing	No.	10	sieve
40 - 100	"	" No.	40	"
12 - 35	"	" No.	200	"

"The percentage passing the No. 200 sieve shall not exceed two thirds of the percentage passing the No. 40 sieve. The liquid limit shall not exceed 25, and the plasticity index shall not exceed 6. Material which does not meet this specification is considered to be susceptible to pumping."

In figure 3, any sample that is susceptible to pumping according to either or both of the criteria is designated as pumping.

While such studies of individual horizons indicate general relationships and are the key to profile studies, it is nevertheless true that soils occur in definite profile relationships. Therefore the actual profile must be considered to gain a fuller appreciation of the probable behavior of the soil under a pavement. For example, it has been previously recognized that the contrast between horizons may account for the concentration of pavement breakup where the grade line shifts from cut to fill.

This contrast is shown in graphical form for the several types of soil parent material in Figure 4. On the two charts the AASHO subgroups are arranged from left to right, with the group index number as a secondary variable plotted along the same axis, where applicable. The horizons for each soil series are arranged downward from the top, and designated by letter and subscript. Trace lines have been drawn to facilitate the comparison of horizons. From these charts the extent of contrast can be visualized. If the trace line is vertical, there is no contrast. If the trace line is sloping or nearly horizontal, varying extremes of contrast are indicated. Also, the general or average position of the horizons indicates the nature of the profile as a whole. Positions at the left indicate the best soils, while positions at the right indicate the poorer soils.

From Figure 4, it may be seen that soils formed from silt over till range from rather good quality with minor contrast to poor quality with considerable contrast.

Soils formed from sands and lake clays show little or no contrast between horizons, although the two groups are at opposite ends of the quality scale. Soils formed from silt over stratifiėd sands show extreme contrast, and are difficult to generalize as their relative quality.

Examination of these diagrams also leads to two other interesting observations. In many cases, while adjacent horizons fall in different subgroups, these subgroups bear some relation to each other. For example, the Milaca, Iron River, and Eldron profiles are composed of an A-4 horizon over an A-2-4 horizon, while in the Shiocton and Elba profiles, this relationship is reversed. These two subgrades are related in the classification system because of si, ilar plastic properties.

In addition to this relationship, it should also be noted that as a general rule the soils plotting to the left, or good quality range, are those that are among the better drained soils, while those falling to the right, or in the poorer subgroups, are also those that are inadequately drained.

To compare the profiles of several soil series, however, some generalization must be attempted. Charts of this nature offer a means of rating profiles according to the probable governing horizon of each. Furthermore, several profiles fall into a given pattern of B-to-C horizon relationship, as already demonstrated. Other profiles have no significant contrast. In the case of still other profiles, the probable position of the grade line

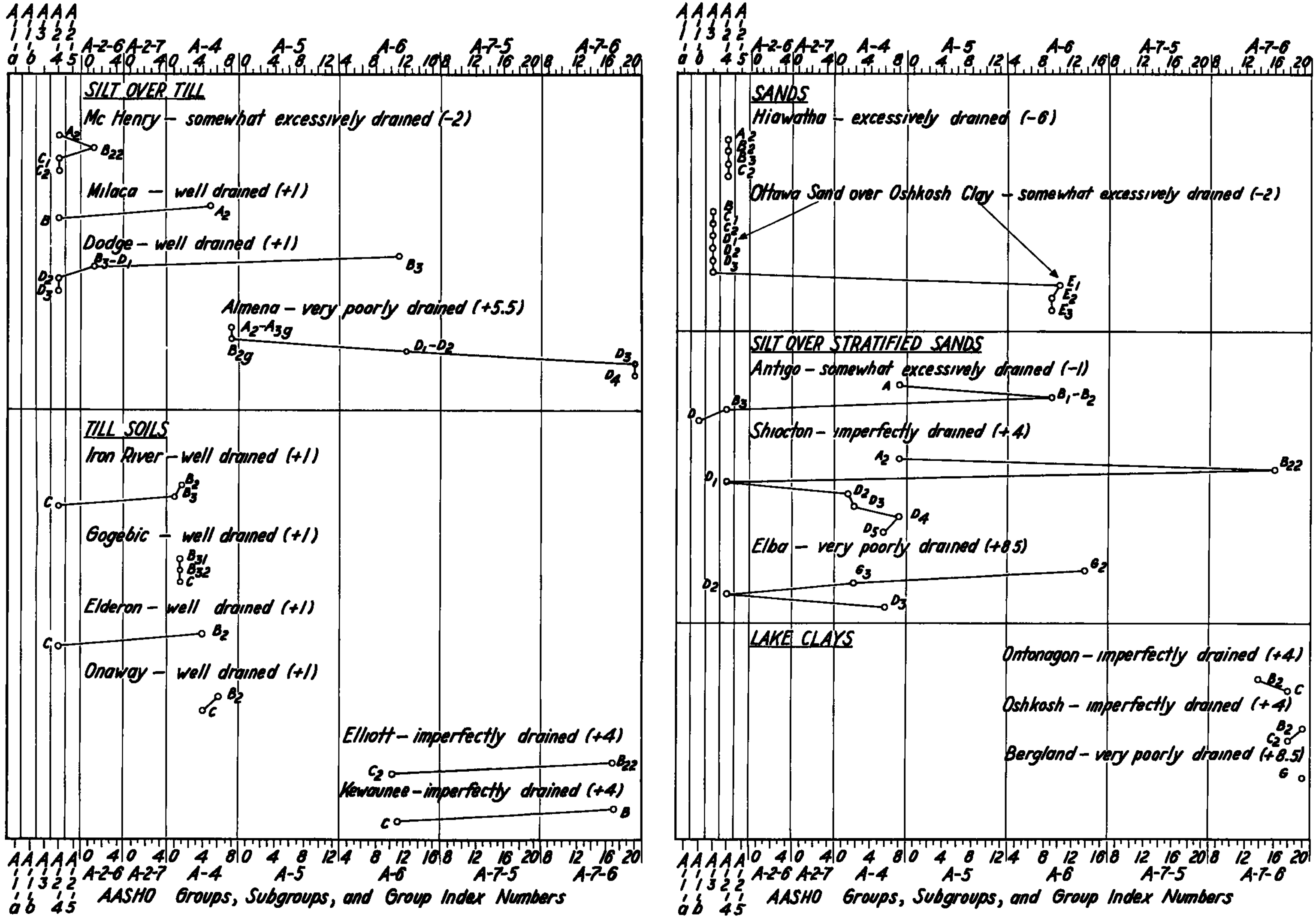


Figure 4. Profile contrast and rating.

relative to the horizons determines which AASHO group the profile as a whole shall be placed in.

Such a generalized rating of the profile as a whole is necessary if the drainage index concept is to be used, as the drainage index refers to the entire profile, not individual horizons. In a similar manner, the profile can be generalized with respect to its frost-susceptibility rating.

The frost-susceptibility rating does not mean that the intensity of frost action will vary with the rating regardless of other conditions. It does mean that if all soils are located similarly with respect to a moisture supply, those with the highest rating will exhibit the greatest frost action. This in turn suggests that if all soils or soil profiles of a given frost-susceptibility rating be arranged with respect to their drainage index, a truer picture might be indicated of the actual amount of frost action to be expected. For example, the actual distress due to frost action would be much less in the Antigo series (somewhat excessively drained) than in the Almena series (poorly drained) although both are in the F-4 category.

Table 2 has been prepared for this purpose. The several profiles are arranged according to their respective drainage indices on the vertical scale, and their generalized frost-susceptibility rating on the horizontal scale. The soil profiles themselves are

TABLE 2

DRAINAGE INDEX RELATED TO FROST-SUSCEPTIBILITY RATING

Drainage Index	F-O	F-1	F-2	F-3	F-4
-6 Excessive			Hiawatha, A-2		
-2 Somewhat Excessive	Ottawa, A-3		McHenry, A-2		
-1 Somewhat Excessive					Antigo, A-6 & A-2
+1 Well Drained			Milaca, A-2 Elderon, A-2 Iron River, A-2 Dodge, A-2		Gogebic, A-4 Onaway, A-4
+2.5 Moderately Well Drained				Dubuque, A-7-6	
+4 Imperfectly Drained				Ontonagon, A-7-6 Oshkosh, A-7-6 Kewaunee, A-7-6	Shiocton, A-7-6 Elliott, A-6
+5.5 Very Poorly Drained					Almena, A-4, A-6, & A-7-6
+8.5 Very Poorly Drained				Bergland, A-7-6	Elba, A-6

represented by their series names and generalized AASHO classifications. This table shows that the soils that are least susceptible to frost action generally occupy the most favorable drainage positions, and that the soils most susceptible to frost action generally occupy the least favorable positions, although there is some overlapping. The chart also shows a similar pattern for the generalized AASHO classification. In those cases where it is difficult to express a generalized rating, more than one group is indicated.

STUDY OF PAVEMENT PERFORMANCE

The objective of this phase was to determine differences in pavement performance ove soil types of various drainage indices. The general procedure was to determine the amount of pavement cracking or to otherwise rate the performance over individual soil bodies, then to correlate this rating with the natural drainage indices of the several soil bodies. On the basis of three types of studies, there appears to be a definite relationship between pavement performance and the drainage index.

The first of these studies consisted of determining the amount of transverse and longitudinal cracking on a concrete road about 10 miles in length. The results are tabulated in two sections because of two different jointing arrangements. On one section, there were no transverse joints, except for construction joints, while on the other section transverse expansion joints were spaced at approximately 50-foot intervals. There was no longitudinal joint on either of the sections. With a detailed soil map in hand, the amount of cracking over each soil body traversed by the highway was determined by walking over the entire length.

When these data are reduced to averages and expressed as the amount of cracking per unit of length, a definite relationship can be noted between the drainage index of the soil bodies and the amount of longitudinal cracking in the pavement. Also, a reasonably good

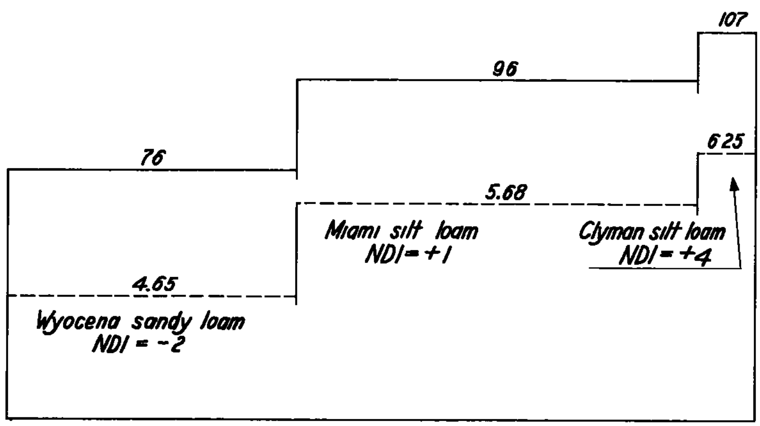


Figure 5. Intensity of pavement cracking related to soil series and drainage, unjointed section. Solid lines and corresponding numbers indicate longitudinal cracking in percentage of total length; broken lines and corresponding numbers indicate transverse cracking expressed as average number of cracks per 100 feet along centerline, NDI is the natural drainage index, expressed numerically.

correlation is shown for the intensity of transverse cracking, although there are some discrepancies here. These relationships are shown in graphical form as Figures 5 and 6, with intensity of cracking increasing upward. The relative distance over each soil type (and therefore over each drainage index) traversed by the highway is shown by the horizontal length of the appropriate lines. The soils are arranged so that the most-poorly drained soils generally are to the right. The greatest intensity of cracking and therefore the poorest performance occurs on these soils.

The second of these studies considered the relationship of the resurfacing requirement to the soil series along a 16-mile section of highway. During 1952 it was found necessary to resurface this highway in certain sections because of excessive breakage. In some cases, a granular base course was required in addition to the bituminous mat, and in

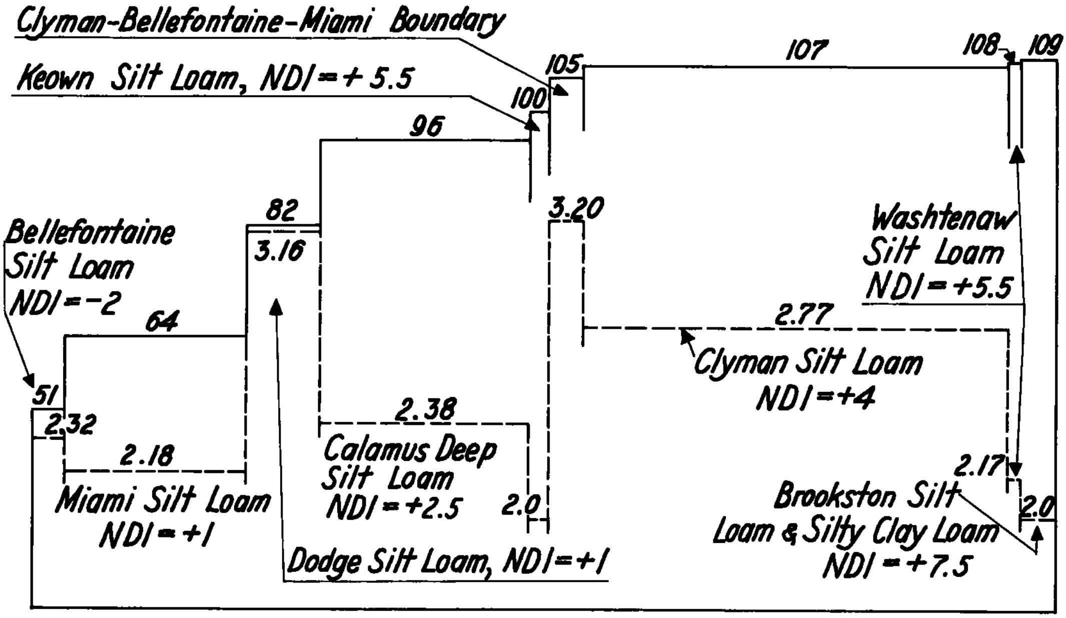


Figure 6. Intensity of pavement cracking related to soil series and drainage - section with transverse joints at 50-foot intervals. Solid lines and corresponding numbers indicate longitudinal cracking in percentage of total length; broken lines and corresponding numbers indicate transverse cracking expressed as average number of cracks per 50-foot slab length; NDI is the natural drainage index, expressed numerically.

other sections, no resurfacing was required at all. Therefore three classes of pavement performance are suggested: (1) no resurfacing, (2) bituminous mat only, and (3) gravel lift course plus bituminous mat.

When the locations of these classes of pavement performance are compared with the soils map (Figure 7), it can be seen that with few exceptions, the portions requiring no resurfacing are on "well-drained" soil. The portions requiring only the bituminous mat were resting on soil types that were "moderately well drained," while the portions requiring the base course as well as the mat were on soil types ranging from "imperfectly" to "very-poorly drained."

The third of these studies was based on a comparison of present pavement conditions with those observed 10 years ago. In 1944, A. T. Bleck of the Wisconsin Highway Commission observed pavement conditions at many places over the state, noting the type of soil as well as general and quantitative information about the pavement (4, 5). These observations and accompanying photographs were made available to the author through the courtesy of Bleck. Several sites were selected for inspection in the spring of 1954, covering a considerable range of soil types. The amount of pavement cracking as well as other evidence of distress was noted, and another photograph taken for comparison.

Because of variations in pavement design, traffic volumes, and local climatic conditions, it is not possible to make such clear-cut comparisons of performance as in the two studies mentioned previously. However, the general trend is similar, with pavements over sand showing the least increase in cracking compared with 1944, and those over silts and clays, poorly drained, showing the most cracking, or even the need for resurfacing, as indicated in the second study. Conditions at two of the seven observation sites are described in the following paragraphs to illustrate this trend.

Figures 8 and 9 illustrate the conditions in 1944 and 1954, respectively, on Plainfield sand (excessively drained, -10). From the photos and recorded observations, it can be seen that cracking has progressed only moderately in the past 10 years. Commercial traffic volume doubled in the same period.

Figures 10 and 11 demonstrate the differences between "well-drained" soils and "poorly drained" soils. The 1944 photo includes Clyde series soil in the foreground (very-poorly drained), and Fox series soil in the background (well drained). In 1944, there was no appreciable difference in the observed behavior of the pavement over the two soils. In 1954, however, quite a change was apparent. The pavement over the Clyde soil has been covered with both a gravel lift and bituminous mat, while the pavement over the Fox soil has not required covering, although there was more cracking in 1954 than in 1944. Again, traffic volumes had about doubled in the intervening period.

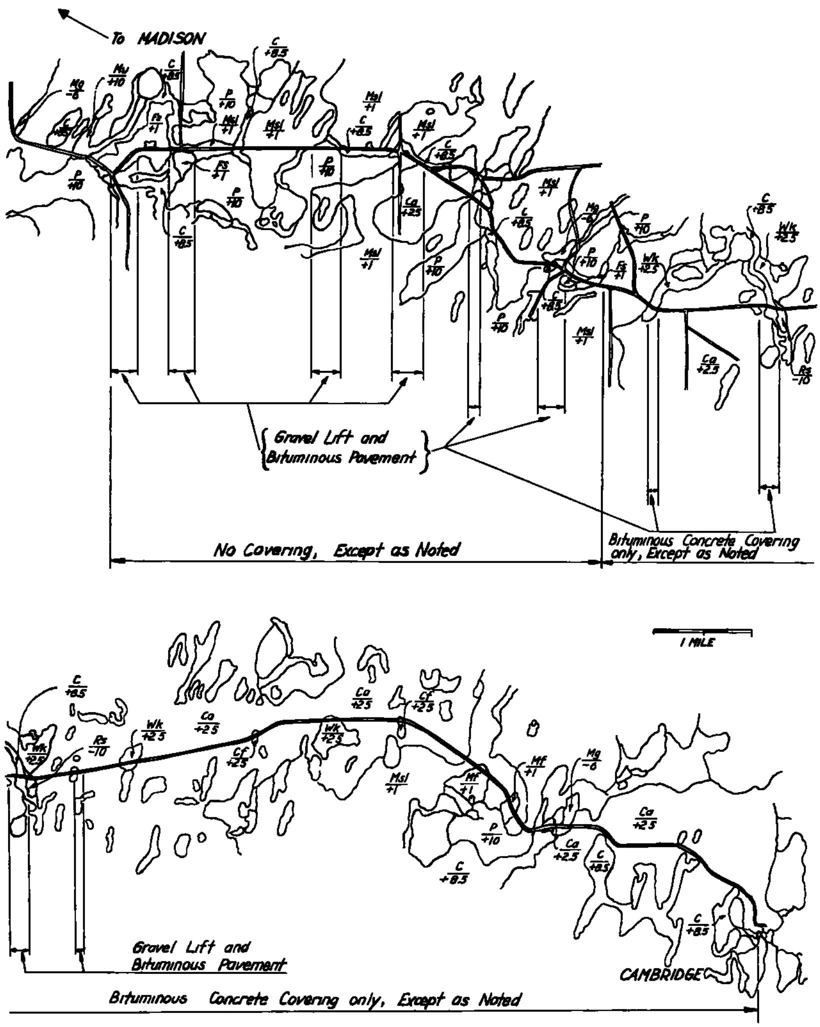


Figure 7. Relationship of soil series and drainage to resurfacing requirements. Original portland cement paving about 1926 resurfacing as indicated in 1952, base map adapted from Dane County Soil Report and Map, Wisconsin Geological and Natural History Survey. Soil-mapping legend: C, Clyde silt loam; Ca, Carrington silt loam; Cf, Carrington fine sandy loam, Fs, Fox silt loam; Mf, Miami fine sandy loam; Mg, Miami gravelly sandy loam; Msl, Miami silt loam; Mu, Muck; P, Peat; Rs, Rodman gravelly sandy loam; and Wk, Waukesha silt loam. The number beneath the mapping symbol is the natural drainage index, expressed numerically.

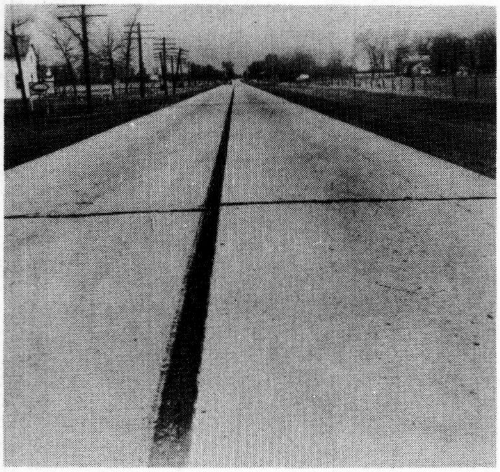


Figure 8. Pavement constructed on Plainfield sand in 1927 without transverse joints - photo taken in 1944 by A. T. Bleck; some transverse cracking at intervals of 120 and 66 feet.

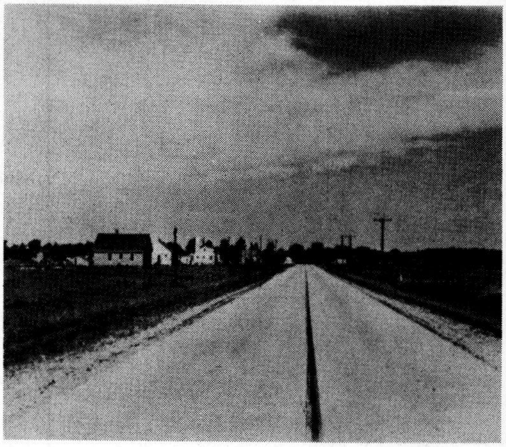


Figure 10. Pavement constructed in 1927 without transverse joints, Clyde soil in foreground, Fox soil in background; crack interval ranges from 15 to 50 feet or more. Photo taken in 1944 by A. T. Bleck.

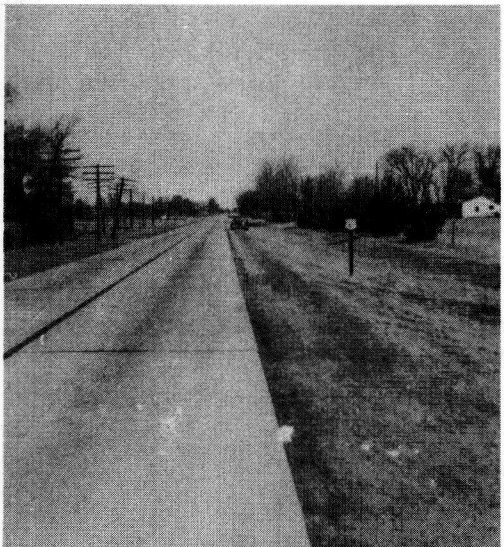


Figure 9. Same pavement as pictured in Figure 8. Pavement rode well in 1954, appeared to be in good condition; in some places, new cracks formed 10 to 15 feet back from older cracks.

Figure 11. Same pavement as pictured in Figure 10. Pavement in immediate foreground is over Miami soil; bituminous pavement and lift course has been placed over pavement constructed on Clyde soil; pavement has not been covered where it rests on Fox soil. Photo taken in 1954.

The traffic volume was somewhat greater than in the case of the pavement constructed over the Plainfield sand.

Figures 10 and 11 also supplement Figure 7 in illustrating the second study.

CONCLUSIONS

The studies upon which this paper is based indicate: (1) there is a reasonably good correlation between the natural drainage index of a soil series and recognized engineering classifications, such as the AASHO classification, the Corps of Engineers frost-susceptibility rating, and pumping criteria; (2) there is a good correlation between the drainage index and actual pavement performance as measured by the observed intensity of cracking of a rigid pavement over several soil types, by resurfacing requirements, and by the observable changes over a period of 10 years; and (3) the drainage-index concept, supplemented by the soil-association concept, may offer an expedient means of organizing the many soil series into workable classifications for engineering purposes.

It is further indicated that the soil textural class is a fairly reliable indicator of the relative susceptibility of a given soil to frost action and pumping action. In this respect, it is important to consider each horizon separately, and not to use the class indicated by the soil mapping unit, which refers to the texture of the surface soil only. Careful study of the soil profile description will indicate the texture of each horizon, as well as other significant information about the soil profile.

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