

# CHARACTERISTICS OF SOME CLAY SOILS FROM WISCONSIN

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Nine clay soil samples representative of local problem soils were tested for physical, physicochemical, and mineralogical properties, and the relationships and correlations among them were determined by analysis of the results. Consolidation tests on compacted samples were studied to obtain consolidation and expansion data for correlation with clay mineralogy, pH of the soil-water system, organic carbon content, and cation exchange capacity. The mineralogy of the soils was determined by X-ray diffraction. The clay mineralogy of soils of glacial origin consists of kaolinite, illite, and illite-montmorillonite in varying proportions, whereas those of dolomitic origin consist of montmorillonite with some kaolinite. The changeable cations present were calcium, magnesium, and lesser amounts of sodium, potassium, and manganese together with traces of iron and aluminum. They were all classed as swelling clays, and the compression index was more sensitive than the expansion index to differences in clay mineralogy. A linear relationship between carbonate content and cation exchange capacity was obtained, and tentative expressions were derived for estimations of cation exchange capacity from values of the plastic or shrinkage limits for soils of similar clay mineralogy. Effectivity of lime in increasing the plastic limit and decreasing the plasticity index of the soil was noted, and soil mineralogy-carbonates and proportions were found to correlate with soil properties.

●THE ENGINEERING PROPERTIES and behavior of fine-grained soils are largely dependent on the type of clay minerals present. For any particular clay mineral, the magnitude of its influence on the properties and behavior of a soil depends not only on the amount of clay present but also on the cation exchange capacity, the exchangeable cations associated with the clay and the relative amount of each, the pH of the soil-water system, and other factors. These influence the interactions between clay particles, which in turn influence the structure, strength, swelling, shrinkage, frost susceptibility, and other characteristics of the natural or compacted soil. Knowledge of pertinent mineralogical and physicochemical properties of a clay soil provides an insight into its characteristics and expected behavior under changes of loading or environment and provides a basis for a rational approach to changing its properties to improve the soil as an engineering material.

This paper presents the results of a study of the physical, mineralogical, and physicochemical properties of various Wisconsin clays that are of concern to highway engineers. The study was directed toward those properties affecting the suitability of the soils as construction materials in roadway components.

The objectives of the study were to obtain a mineralogical and physicochemical characterization of the soils and to obtain correlations between results of relatively simple physical tests and those of more complicated or time-consuming mineralogical and physicochemical tests.



## SOILS INVESTIGATED

Nine soils provided by the Wisconsin Department of Transportation were studied. These are materials that are considered to be representative of clay soils in Wisconsin and that present problems in highway construction. The materials are from the substrata of the Kewaunee, Oshkosh, Morley, Fayette, and Ontonagon series. The approximate sample locations of these soils, designated by the letters A through I in this report, are shown in Figure 1.

Soil A is of the Kewaunee series; the parent material is a brownish calcareous clay deposited originally as lacustrine sediments that were subsequently reworked and re-deposited by glacial ice. Soil B is of the Oshkosh series and is a reddish lacustrine clay. Soil C is of the Morley series and is a yellowish-brown glacial till. Soil D is of the Fayette series and consists of a red clay residuum formed from dolomite. Soils F, E, G, H, and I are all of the Ontonagon series and are reddish-brown lacustrine clays.

## TEST METHODS

The physical properties of the soils were determined, where applicable, by standard ASTM methods (1). Consolidation tests were performed on remolded compacted soil specimens. The samples were placed in a consolidometer, flooded, and allowed to come to equilibrium under a 70.8-psf load. The applied loads were then doubled every 24 hours until a maximum of 36,000 psf was reached. Rebound was obtained by reducing the load to a quarter of the preceding increment every 24 hours. The primary purpose of these tests was to obtain consolidation and expansion data for correlation with clay mineralogy and other parameters.

The pH of the soil-water system (1:1 ratio by weight) was measured with a glass electrode pH meter. The organic carbon content of the soils was determined by the Walkley-Black method (3, pp. 1372-1376). The carbonate content was determined by the gravimetric (weight loss) method. The apparatus used was modeled after that discussed by Furman (4, pp. 238-239). The cation exchange capacity was determined by the ammonium acetate method described by Davidson and Sheeler (5). Identification of exchangeable ions and the relative amounts were made on the ammonium acetate extracts obtained in the leaching for the cation exchange capacity test. Atomic absorption was used for calcium, magnesium, iron, and manganese; flame emission for sodium and potassium; and solution transmission for aluminum.

The lime retention point may be closely approximated as the lime content at which the maximum plastic limit is attained (6). In this study, the lime retention point was found by mixing a commercial hydrated lime to the soils at 0, 1, 2, 3, 4, and 5 percent by weight, mixing with distilled water in excess of the plastic limit, sealing in a jar for 24 hours, and then determining the plastic limit. The plastic limit versus lime content was plotted to obtain the lime retention point.

The mineralogy of the soils was determined by X-ray diffraction by using copper  $K\alpha$  radiation. Soil fractions with particle sizes of  $d < 2\mu$ ,  $0.2 < d < 2\mu$ , and  $d < 0.2\mu$  were obtained by the procedure discussed by Black (7, p. 680). The preparation of X-ray samples and the supplementary tests in general followed the procedures discussed by Carroll (8).

## RESULTS

### Index and Chemical Properties

Table 1 gives the results of index property and classification tests and of various chemical tests for the soils. The soils are all A-6 or A-7 in the AASHTO classification system.

Soils A and C, for which the parent materials were glacial tills, have much higher carbonate contents than do soils B, F, G, H, and I, which were derived from lake deposits. The absence of carbonates in soil E, a lacustrine clay, and soil D, a residuum derived from dolomite, is consistent with their low pH values. For those soils containing carbonates, the cation exchange capacity decreases with increasing carbonate content.

The predominant exchangeable cations are calcium and magnesium for all soils. The ratio of Mg/Ca (each in terms of milliequivalents) is about 1 for soils B and E, 0.7 for soil D, and in the range of 0.3 to 0.4 for the remaining soils. There are measurable amounts of sodium, potassium, and manganese and traces of iron and aluminum.

### Mineralogy

The mineralogical analyses of the soils were by X-ray diffraction. Analyses of samples of total soil materials showed that the primary nonclay minerals are quartz, plagioclase feldspars, calcite, and dolomite. X-ray charts for soils D and E showed no calcite or dolomite peaks; chemical analyses revealed only a trace of carbonates. The X-ray chart for soil F is shown in Figure 2. This is typical of the results obtained although peak intensities vary and some additional or missing peaks may show on charts for the other soils.

Analyses of clay minerals were made with oriented samples of materials less than  $2 \mu\text{m}$ , between 2 and  $0.2 \mu\text{m}$ , and less than  $0.2 \mu\text{m}$ . The same peaks, with differing intensities, occurred for all soils except the soil D. The 7.1- to 7.2-Å peaks suggest kaolinite or chlorite; the 10-Å peaks illite or halloysite; the 14-Å peaks chlorite, vermiculite, montmorillonite, or a mixed layer clay; and a 12.5-Å peak for soil D suggests a montmorillonite. Additional X-ray diffraction studies on samples first subjected to supplementary tests were required to resolve which clays were present. After heating to 110 C, the 10-Å peaks should shift toward the 7.2-Å range if halloysite is present. Also, after treatment at 600 C, the halloysite structure should be destroyed (8). The 10-Å peaks were stable for both treatments, indicating illite.

Heat treatment to 600 C caused the 7.2-Å peaks to disappear, which may occur for both kaolinite and chlorite. However, heating to 700 C should cause 14-Å chlorite peaks to intensify. In this case they disappeared (collapsed to 10 Å). Therefore the 7.2-Å peak indicated kaolinite, and the 14-Å peak indicated some mineral other than chlorite.

The 14-Å peaks were more difficult to resolve. These could be due to vermiculite, a mixed-layer clay, or both. A common treatment for distinguishing between expandable and nonexpandable clays is to allow adsorption of certain organic complexes, e.g., ethylene glycol. A montmorillonite will give a peak at 17 Å; a mixed-layer clay containing montmorillonite will give a peak at some lesser spacing. Ethylene glycol treatment of the soils caused the 12.5-Å peak of soil D to shift to 17 Å, indicating montmorillonite. For the other soils the 14-Å peak shifted to the range of 16.2 to 16.4 Å. Vermiculites with interlayer ions other than magnesium may expand to the 16-Å region (9, p. 316). Therefore, the behavior of the 14-Å peaks with ethylene glycol could be due to a mixed-layer clay, vermiculite, or both.

Heating of a montmorillonite to temperatures in excess of 300 to 400 C will cause an irreversible collapse to a spacing around 10 Å (8). Heating to 600 C will cause collapse of vermiculites, but there is partial rehydration upon cooling. Heat treatment of the soils to 600 C led to a peak near 13.6 Å, which was considerably less intense than the 14-Å peaks, for all but soil D. The 13.6-Å spacing is close to the third hydration state of 13.8 Å for vermiculite (8). Therefore, this test indicates the presence of some vermiculite in all but soil D. For this soil 600 C led to a fairly sharp 10-Å peak, the collapsed spacing for montmorillonite. For the other soils the relative intensity of the 10-Å peak increased under 600 C treatment, which could be due to the presence of montmorillonite or unrehydrated vermiculite. Treatment to 700 C caused permanent collapse of 12.5- and 14-Å peaks to 10 Å, ruling out chlorite, which would intensify at 14 Å at that temperature.

X-ray diffraction of water-wetted samples caused expansion of the 12.5-Å peak of soil D to more than 20 Å, again indicating montmorillonite. The other soils showed broad peaks, with peaks or hints of them in the 15- to 16-Å range and expansion to the 18- to 20-Å range. Calcium vermiculites expand to about 15.3 Å in water (9, p. 320). Therefore, the 15- to 16-Å peak again indicates the presence of vermiculite. The larger expansion indicates the presence of montmorillonite, probably in an illite-montmorillonite mixed-layer clay.

In summary, soil D contains primarily kaolinite and montmorillonite. The other soils contain kaolinite, illite, a mixed-layer clay, and some vermiculite. When esti-

mates of the relative quantities of each mineral were made, the mixed-layer and vermiculite were taken together as an illite-montmorillonite-vermiculite constituent because it was impossible to resolve components of the 14.3-Å peaks for untreated samples.

A rough estimate of the relative amounts of the various clays was made by using integrated peak intensities and mass absorption coefficients of the minerals. The basic method is discussed by Norrish and Taylor (10). The procedure was subject to considerable error because, in our case, there was overlapping of peaks for the minerals. The portion assigned to each and the level of background radiation must be estimated in each case. The integrated peak intensity  $I$  for each peak was taken as peak height  $H$  times peak width  $W$  at  $H/2$ . Average values of mass absorption coefficients  $A$  for various minerals are given by Carroll (8). For copper  $K\alpha$  radiation these are 30 for kaolinite, 55 for illite, 42 for montmorillonite, and 59 for mixed-layer clays. These values were used to estimate the relative amounts of each clay mineral for each soil. Table 2 gives the results for the various size fractions of the soils. It must be emphasized that these are quite rough estimates inasmuch as there are several possible sources of error. However, they do give an indication of the relative abundance of the various clay minerals in the soils.

Similarly, estimates were made of the relative proportions of calcite and dolomite in the carbonates of the soil. Mass absorption coefficients of 71 for calcite and 50 for dolomite were used (8). The results are also given in Table 2.

### Lime Retention

Table 3 gives the lime retention point of the soils and the effects of lime at the retention point on the Atterberg limits. The lime retention point is that percentage of lime content, by weight, at which the maximum plastic limit is reached. In all cases the lime caused a decrease in the liquid limit for the A-7 soils and an increase for the A-6 soils. The change in plastic limit was more pronounced and the plasticity index was reduced in all cases. The shrinkage limit was increased in all cases. In general, Atterberg limits increased with increasing clay content.

### Consolidation Characteristics

Plots of  $e$  versus  $\log(p)$  for the remolded compacted soils were used to determine compression and expansion indexes. These are given in Table 1. The estimated pre-consolidation pressures were in the range of 2,500 to 3,000 psf for all but soil D, which had a pressure of about 5,500 psf. The coefficients of consolidation, by the log time-fitting method, varied from about  $1 \times 10^{-4}$  to  $5 \times 10^{-4}$   $\text{cm}^2/\text{sec}$  over the pressure range for each of the soils.

## DISCUSSION OF TESTS

### Atterberg Limits

Figure 3 shows the relationships between the Atterberg limits and clay content (percentage  $< 2\mu$ ) for the soils studied. In their study with artificial soil mixtures, Seed, Woodward, and Lundgren (11) showed that for a given clay mineral composition the liquid limit should vary linearly with clay content. For our soils, the data for those of similar clay mineralogy give a roughly linear plot, but differences in relative proportions of the various minerals cause considerable scatter.

The plastic limit is less dependent on clay mineral composition. Seed, Woodward, and Lundgren show a hypothetical relationship between plastic limit and clay content, which gives a linear plot with plastic limit increasing from 20 to about 50 between clay contents of 40 and 100 percent. The data for our study fall within the hypothetical range they gave. Again, differences in clay mineral proportions cause deviations from a linear plot.

Figure 3 shows that the shrinkage limit ( $w_s$ ) versus clay content ( $C$ ) is nearly linear for the soils studied. A least squares fit of the data yields the following expression:

Figure 2. X-ray trace of soil F (total sample, random orientation).

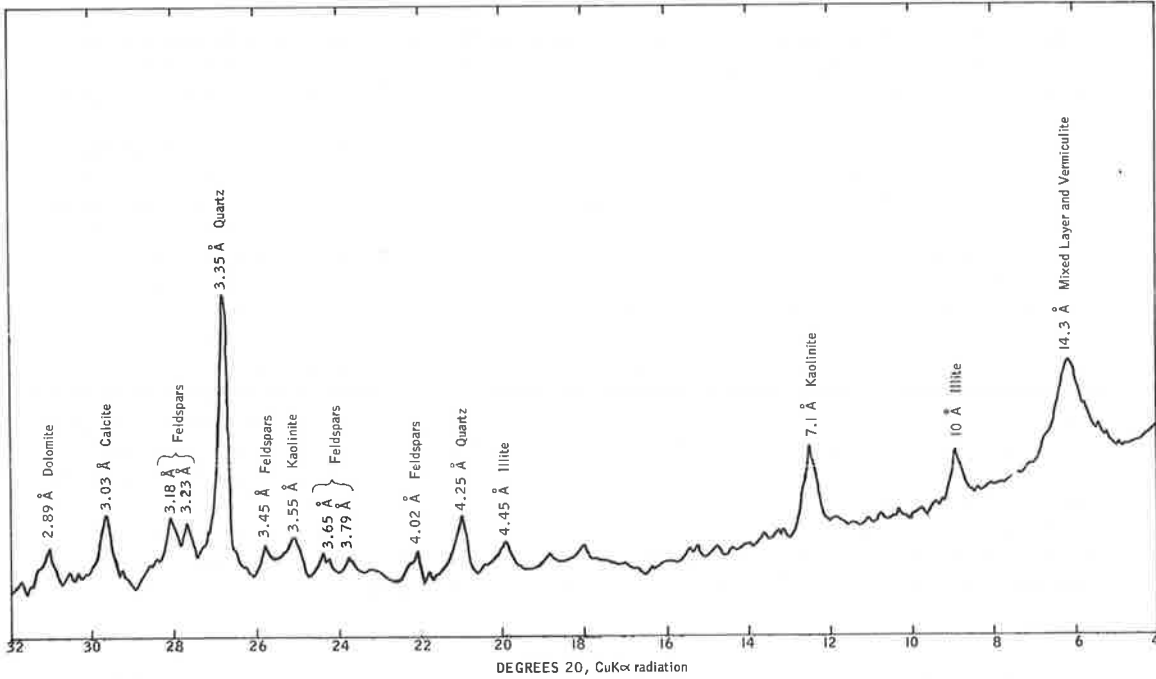


Table 2. Clay mineral and carbonate composition.

Soil	Percentage of Carbonates		Clay Minerals	Percentage of Total Clay in Size Fraction		
	Calcite	Dolomite		<2 $\mu$	2 - 0.2 $\mu$	<0.2 $\mu$
A	45	55	Kaolinite	4	12	1
			Illite	26	42	21
			Mixed-layer	70	46	78
B	10	90	Kaolinite	6	15	2
			Illite	47	28	27
			Mixed-layer	47	57	71
C	30	70	Kaolinite	12	17	3
			Illite	49	50	39
			Mixed-layer	39	33	58
D	—	—	Kaolinite	5	9	3
			Montmorillonite	95	91	97
E	—	—	Kaolinite	4	8	1
			Illite	33	32	27
			Mixed-layer	63	60	72
F	70	30	Kaolinite	7	16	4
			Illite	30	32	18
			Mixed-layer	63	52	78
G	60	40	Kaolinite	7	16	3
			Illite	22	25	19
			Mixed-layer	71	59	78

Table 3. Effect of lime at the retention point on Atterberg limits.

Soil	Lime Retention (percent)	Atterberg Limits (percent)			
		Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit
A	2.7	34	28	6	21.6
B	2.5	49	35	14	24.0
C	2.5	40	34	6	21.5
D	2.0	56	42	14	17.5
E	2.5	50	41	9	28.8
F	2.0	61	53	8	26.8
G	2.0	59	68	11	27.4
H	2.0	68	46	22	25.8
I	2.0	54	46	8	25.9

$$w_a = 5.96 + 0.158C \quad (1)$$

In Eq. 1 the standard error  $\bar{s}$  is 1.6, and the correlation coefficient  $\gamma$  is 0.87. The error is somewhat larger than that expected in the shrinkage limit test, but Eq. 1 does yield a suitable approximation of the shrinkage limit for the soils studied. No meaningful correlation could be found between the shrinkage limit and the plastic or liquid limits.

Figure 4 shows the correlation of the liquid limit with the compression index  $C_c$  and expansion index  $C_e$  for the remolded compacted soils. Least squares fittings give two parallel lines that can be expressed by

$$C_c = 0.25 \frac{w_L}{100} + 0.05 \quad (2)$$

and

$$C_e = 0.25 \frac{w_L}{100} - 0.06 \quad (3)$$

The standard errors and correlation coefficients are  $\bar{s} = 0.02$  and  $\gamma = 0.86$  for Eq. 2 and  $\bar{s} = 0.02$  and  $\gamma = 0.88$  for Eq. 3. The estimated values of  $C_c$  and  $C_e$  are within the probable accuracy of determining values from the  $e$ - $\log(p)$  plots. The relationships may be of value in estimating deformations in compacted embankments.

In general, the cation exchange capacities of the soils increase with increasing values of Atterberg limits, as shown in Figure 5. The curves are for soils of similar mineralogy; in each case the data point to the far right is for soil D with its different clay constituents. In their studies of Iowa loesses (all of similar clay mineralogy) Davidson and Sheeler (5) found somewhat similar behavior. In their discussion they note that the relationships become nearly linear for soils containing lower, nearly equal amounts of carbonates. The cation exchange capacity seemed to decrease with increasing carbonate, and they concluded that the curvilinear relationships observed were due to the presence of carbonates in the soils.

#### Cation Exchange Capacity

Figure 6 shows the relationship between equivalent calcium carbonate content and the cation exchange capacity. For the data available, excluding soils D and E, which had only a trace of carbonates, a linear relationship was obtained. Unfortunately, none of the soils tested had carbonate contents in the 20 to 30 percent range. By using the data available, a least squares fit was made to obtain the expression

$$CEC = 35.0 - 0.589 (\text{CaCO}_3) \quad (4)$$

where

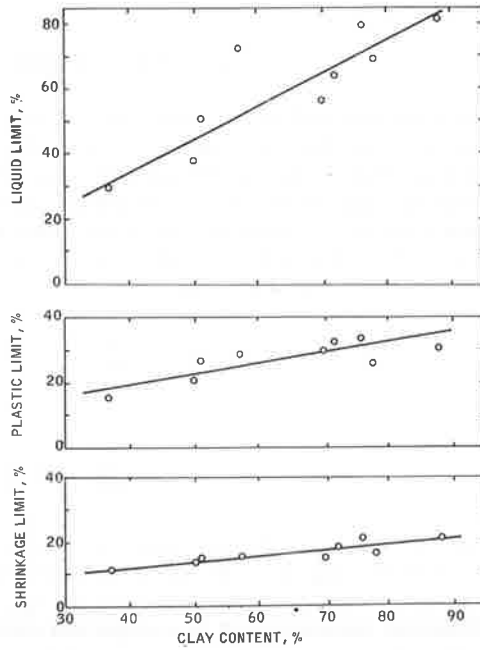
CEC = cation exchange capacity, meq/100 gram, and  
 $\text{CaCO}_3$  = percentage of equivalent calcium carbonate.

The data points used in Figure 6 were averages of at least two or three tests each. The scatter of data about the least squares fit is less than the differences to be expected in the testing procedures. The standard error in Eq. 4 is  $\bar{s} = 1.2$  and the correlation coefficient is  $\gamma = 0.99$ . Additional soils of similar clay mineralogy would be required to test the equation in the 20 to 30 percent carbonate range.

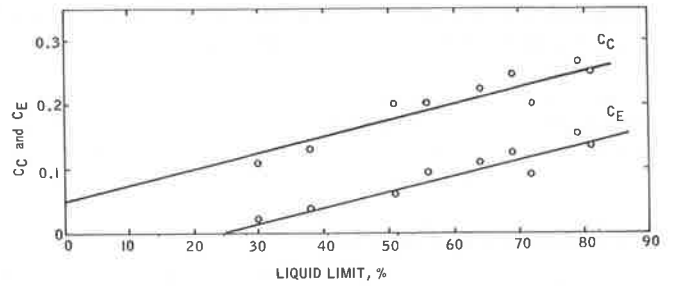
Because carbonate contents appear to affect the relationship between Atterberg limits and cation exchange capacity (5), it was felt that some expression for the limit versus cation exchange capacity might be obtained. In studying various possibilities, it was observed that the plastic limit and the shrinkage limit were nearly linear with respect to the product of the carbonate content and cation exchange capacity. Least squares fits of the data gave the following equations:

$$w_p = 50.5 - 0.0712 [(CEC) \times (\text{CaCO}_3)] \quad (5)$$

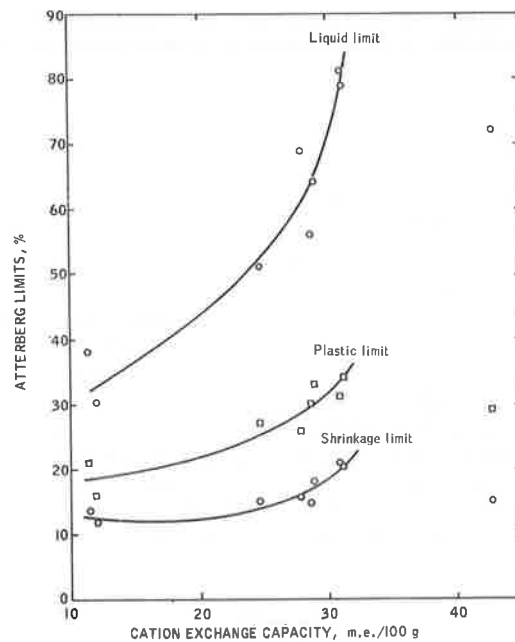
**Figure 3. Atterberg limits versus clay content.**



**Figure 4. Compression and expansion indexes versus liquid limit.**



**Figure 5. Atterberg limits versus cation exchange capacity.**





$$w_s = 30.4 - 0.0409 [(CEC) \times (CaCO_3)] \quad (6)$$

These equations and Eq. 4 were used to derive the following expressions for the plastic and shrinkage limits in terms of cation exchange capacity:

$$w_p = 50.5 - 4.21 (CEC) + 0.120 (CEC)^2 \quad (7)$$

$$w_s = 30.4 - 2.42 (CEC) + 0.069 (CEC)^2 \quad (8)$$

Values of cation exchange capacities calculated by Eqs. 4, 7, and 8 and those obtained in laboratory tests are given in Table 4 for comparison. Although soil E, with no carbonate, was not used in the above derivation, the calculated cation exchange shows good agreement with the measured value. Soil D, with its different clay mineralogy, shows no agreement. Of the others, soil B shows the largest deviation and is overestimated. This material differs from the others in which carbonate is present in that the pH is lower, the exchangeable Mg/Ca ratio is higher, and the relative amount of dolomite is higher. The pH for soil B is 8.0 and for the others ranges from 8.2 to 8.5; the Mg/Ca ratio is about 1 for soil B and ranges from 0.3 to 0.4 for the others; and the dolomite-calcite ratio is 9 for soil B and ranges from 0.4 to 2.5 for the other soils. These differences may account for the overestimation of cation exchange capacity.

According to both Eqs. 7 and 8, the minimum plastic and shrinkage limits would occur at a cation exchange capacity of about 17.5 meq/100 gram, or a carbonate content of about 30 percent. Additional study with more soils, particularly those with carbonate contents in the 20 to 30 percent range, would be required to validate the trends observed and to adjust the relationships for better accuracy.

### Soil Mineralogy

With the exception of the residual soil D, the clay mineralogy of all the soils tested is similar, as given in Table 2. Because the estimates of relative proportions of each clay mineral present are subject to several error sources, discussion of the effects of clay mineralogy on soil properties must be qualitative rather than quantitative.

The difference between the properties of soil D and those of the other soils can be attributed to the difference in clay minerals present. The relatively high cation exchange capacity and liquid limit, at comparable clay contents, for soil D can be attributed primarily to presence of montmorillonite as the predominant clay mineral.

Soils B and C, with nearly the same percentage of less than 2- $\mu$ m material, have quite different properties. Both have about the same proportion of illite, but soil C has about twice as much kaolinite and has less of the illite-montmorillonite-vermiculite constituent. This difference in clay mineral contents accounts for the smaller values of cation exchange capacity and Atterberg limits for soil C. Kaolinite has the least cation exchange capacity of the clay minerals and generally has lower values of Atterberg limits. The effects on the plastic and shrinkage limits are less than on the liquid limit. Compression and expansion indexes are less for soil C with its higher kaolinite and lower mixed-layer clay contents; the effect is about the same for both indexes. Another factor may be the higher carbonate content of soil C. Part of this is in the less than 2- $\mu$ m material, and, probably, the actual total clay mineral content is less.

Soils A and C have about the same cation exchange capacity and carbonate contents, but quite different clay size percentages. Soil A, with less clay-size material, has a considerably larger portion of the mixed-layer clay mineral and less of the kaolinite and illite clays. This accounts for its higher relative cation exchange capacity. Soil C, with its greater total clay content, has somewhat larger values of the Atterberg limits, whereas soil A, with its lower clay content but higher proportion of mixed-layer clay, has nearly as large a compression index as soil C. The expansion index appears to be less affected by the difference in clay mineralogy than is the compression index.

Soils A and G have about the same relative proportion of mixed-layer clay and comparable proportions of illite and kaolinite. Soil G, with about twice as much clay-size

Figure 6. Cation exchange capacity versus carbonate content.

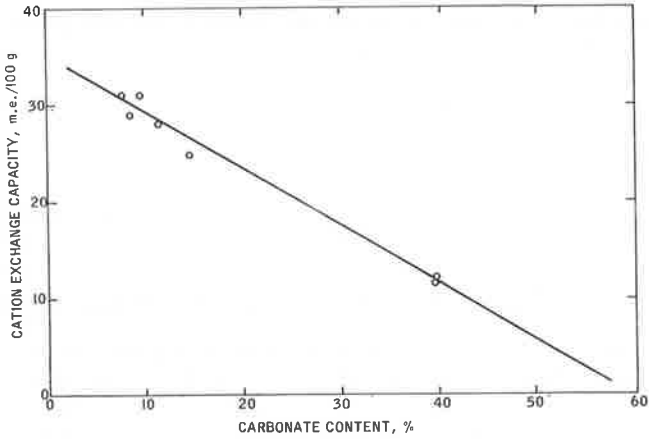


Table 4. Estimated and measured values of cation exchange capacity.

Soil	Cation Exchange Capacity (meq/100 gram)			
	Measured	Estimated by CaCO <sub>3</sub> Content	Estimated by Plastic Limit	Estimated by Shrinkage Limit
A	12.0	11.7	13.0	11.3
B	24.7	26.4	28.1	26.6
C	11.4	11.8	9.7	9.6
D	42.7	—	28.9	26.7
E	28.6	—	29.2	26.5
F	30.9	29.4	29.6	30.6
G	28.9	29.9	30.3	28.9
H	31.1	30.5	30.6	30.0
I	27.9	28.3	27.7	27.4

material, has more than twice the cation exchange capacity. Again, the larger carbonate content of soil A influences the difference. The values of liquid limit, plastic limit, and plasticity index are also slightly more than twice as large for soil G as for soil A. The compression index for soil G is double that for soil A. Again, the expansion index appears to be more greatly affected by the total clay content and less affected by relative proportions of clay minerals than is the compression index.

Soils E and G have about the same clay-size content. Soil G contains more carbonates, less illite, and more kaolinite and mixed-layer clay. The cation exchange capacities are nearly equal, reflecting the compensating effects of differences in mineralogy. The Atterberg limits are greater for soil G, the liquid limit being affected more by clay mineralogy differences than the others. The compression indexes are nearly the same, again reflecting compensating effects of mineralogy. The expansion indexes are also quite close.

Soils E and F have comparable proportions of the various clay minerals, but soil F has a greater total clay-size content. This results in larger values of cation exchange capacity and of Atterberg limits. The differences are not so large as might be expected, probably because of the larger carbonate content of soil F. Both the compression index and the expansion index are larger for soil F; again the expansion index appears to be more affected by differences in total clay content.

The amount of lime required for maximum increase in plastic limit (lime retention point) does not appear to depend on clay content or clay mineralogy to any discernible degree. The data suggest that larger lime retention points are obtained for the soils with larger carbonate contents (A and C) and the soils with larger exchangeable Mg/Ca ratios (B and E). Soils A, B, and C also have a larger proportion of dolomite in the total carbonates than do the other soils. The commercial lime used in the study was of the high calcium variety. The use of a dolomitic lime could very well have given different results. For the soils with a high Mg/Ca ratio, and the lime used, replacement of exchangeable Mg by Ca from the lime may help explain the greater lime requirements. The effect of total carbonate content and relative proportions of calcite and dolomite would require more study with a wider range of soils and limes.

### Chemical Properties

The relationships of cation exchange capacity and carbonate content to various other properties have been discussed. Also, some possible effects of relative amounts of exchangeable calcium and magnesium have been suggested. The amounts of other exchangeable cations (sodium, potassium, manganese, iron, and aluminum) appear to be too small to have much effect on other properties, or the effects are masked by other factors.

The organic carbon content varied from 0.12 to 0.57 percent, averaging 0.32 percent for the soils studied. This range of values was not great enough to cause any observable effects on soil properties.

The pH values obtained ranged from 5.8 to 8.5. The range was 8.2 to 8.5 for the majority of the soils. Lower values were obtained for the soils with higher Mg/Ca ratios and dolomite-calcite ratios; i.e., for soil D pH = 5.8 and Mg/Ca = 0.7; for soil E pH = 7.3 and Mg/Ca = 1; and for soil B pH = 8.0, Mg/Ca = 1, and dolomite-calcite = 9. For the other soils, pH ranged from 8.2 to 8.5, the Mg/Ca ratios were from 0.3 to 0.4, and the dolomite-calcite ratios were from 0.4 to 2.3. Any effects of pH on soil properties were masked by the effects of other factors.

### SUMMARY AND CONCLUSIONS

Samples of several Wisconsin soils, typical of problem soils encountered in highway construction, were furnished by the Division of Highways, Wisconsin Department of Transportation. A testing program was conducted to determine physical, physico-chemical, and mineralogical properties of the soils, and the results were analyzed to determine relationships and correlations among the various soil properties. Results and conclusions for the soils tested follow.

1. The clay mineralogy of the soils derived from glacial tills and glacial lake deposits consists of kaolinite, illite, and illite-montmorillonite-vermiculite mixed-layer clays in varying proportions and amounts. The one residual soil, derived from a dolomite, consists primarily of montmorillonite with some kaolinite.

2. The predominant exchangeable cations associated with all the soils are calcium and magnesium, with lesser amounts of sodium, potassium, and manganese and traces of iron and aluminum. The Mg/Ca ratios are from 0.3 to 0.4 for most of the soils but are from 0.7 to 1.0 for those with a lower pH or higher dolomite portion of total carbonates. All but two of the soils are calcareous.

3. The Atterberg limits are roughly linear with clay content, liquid limit being most affected by clay mineralogy. An empirical relationship between the shrinkage limit and clay content was obtained.

4. Consolidation tests on the remolded compacted soils show that all may be classed as swelling clays. Linear correlations between the liquid limit and the compression and expansion indexes were obtained. The compression index appears to be more sensitive to differences in clay mineralogy.

5. For the soils containing carbonates, within the accuracy of experimental determination of either property, a linear relationship between carbonate content and cation exchange capacity was obtained. The effect of carbonates on the relation between cation exchange capacity and the Atterberg limits was considered to derive tentative expressions to permit estimation of cation exchange capacity from the values of the plastic or shrinkage limits for the soils of similar clay mineralogy.

6. Lime is effective in increasing the plastic limit and decreasing the plasticity index of all the soils. The lime retention point appears to be more dependent on carbonate contents and exchangeable cations than on clay mineralogy or clay content. Lime at the retention point causes an increase in liquid limit for the A-6 soils and a decrease for the A-7 soils.

7. The soil mineralogy, carbonates and proportions of various clay minerals, can be qualitatively correlated with other soil properties.

#### ACKNOWLEDGMENTS

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