Summarization and Comparison of Engineering Properties of Loess in the United States

J. B. SHEELER, Associate Professor of Civil Engineering, Iowa State University

•LARGE deposits of loess are found in many parts of the United States, but published values of the engineering properties of loess are relatively scarce. The data in this paper were gathered to indicate similarities and compare the properties of loess from one area with another.

Loess is composed primarily of rather loosely arranged angular grains of sand, silt, and clay. Silt is usually the dominant size. Calcite is also generally present in amounts ranging from zero to more than 10 percent of the total soil.

The aeolian hypothesis of loess deposition is compatible with the physical characteristics of undisturbed loess masses. This hypothesis states that fine-grained material was transported, sorted, and redeposited by wind action and thus became loess. During deposition, moisture and clay minerals are believed responsible for cementing the coarser grains together to form a loose structure. The loess is therefore subject to loss of shear strength due to water softening the clay bonds and to severe consolidation caused by a combination of loading and moisture.

Loess is usually thought of as an aeolian material that was deposited thousands of years ago and has remained in place since the time of deposition. Loess that has been eroded and redeposited is often referred to as redeposited loess, reworked loess or more simply as a silt deposit. This implies that the word loess indicates an aeolian soil, undisturbed since deposition. Certain engineering properties of loess, such as shear strength, are quite drastically changed by erosion and redeposition. The data presented in this paper are from samples of loess that have been undisturbed since deposition, to the best knowledge of the author, and the term loess is used in this context.

IDENTIFICATION

Loess may be identified primarily by its color and particle size. The structure and the unique ability to stand in vertical cuts are also distinguishing characteristics. The color varies from yellow to reddish brown with a buff color being the most common. The grains are almost all smaller than the upper limit of silt (0.074 mm), and there is a complete absence of pebbles or rocks. However, it is not uncommon to find fairly soft calcium carbonate concretions about the size of a pea. These concretions have formed since deposition by solution and subsequent precipitation of the carbonate. They can be easily identified by their rather violent reaction with hydrochloric acid.

The structure of the loess is typically open and contains many void spaces. Grape-like clusters of balls of silt are sometimes observable. Most of the grains are coated with thin films of clay, while some of the grains are coated with a mixture of calcite and clay. Individual silt-sized particles of calcite can also be found well dispersed throughout the mass of loess. The clay coatings are apparently the major cementing agent. Some authors believe that calcium carbonate also contributes to the cementation of particles into the typical open structure.

Paper sponsored by Ad Hoc Committee on Loess and presented at the 45th Annual Meeting.

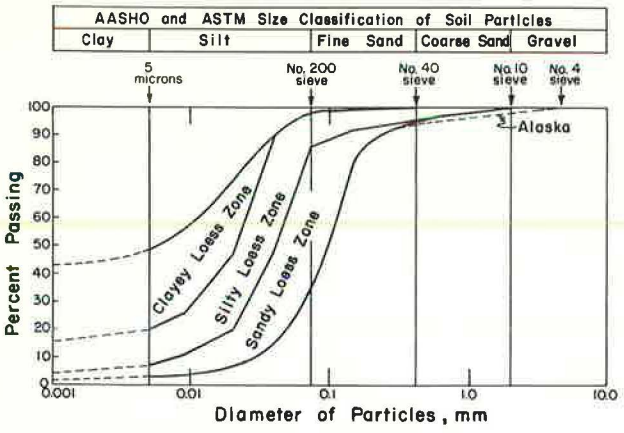

Figure 1. Gradation characteristics of loess in the United States.

MECHANICAL ANALYSIS

The gradation characteristics of loess are shown in Figure 1. All gradation curves fall within the confines of the limiting boundaries, with the exception of the Alaskan loess. This loess appears to be slightly more coarse than that found in the other states. All of the United States loess is smaller than 2.00 mm (No. 10 sieve), except the Alaskan loess, which for several samples has an upper limit of 9.53 mm (3/8 in. sieve); for most samples the upper limit is 4.76 mm (No. 4 sieve). It is thought that the particles larger than 2.00 mm are carbonate concretions, although the data furnished the author did not mention concretions.

The general shape of a loess gradation curve is similar to that of the boundary curves shown in Figure 1. The area within the boundaries is arbitrarily divided into clayey loess, silty loess, and sandy loess, after Holtz and Gibbs (10). These investigators found that for loess from the Missouri River Basin area, 71 percent of the samples were classified as silty loess, 21 percent as clayey loess, and 8 percent as sandy loess.

SPECIFIC GRAVITY

The specific gravity of loess in the United States varies between 2.57 and 2.79. The range is much smaller in local areas; for example, in Iowa it is from 2.68 to 2.72, in Nebraska 2.57 to 2.69, in Tennessee 2.65 to 2.70, in Mississippi 2.66 to 2.73, and in Alaska 2.67 to 2.79. These local variations are most likely due to the variations in the type and quantity of mineral content.

ATTERBERG LIMITS

Plasticity data for various locations are given in Figure 2. Clevenger (5) indicates that sandy loess values lie in an area covering the lower end of the A-line below the Cl-ML zone, silty loess lies in an area straddling the A-line up to a LL of about 34, and clayey loess values lie in an area just above the A-line.

Plasticity data representative of loess from various parts of the United States are plotted as a function of five-micron clay content in Figure 3. The results are similar to those found by the author for Iowa loess (8, 9, 20). However, the additional points provided by the low clay content Alaskan loess and the high clay content Illinois loess indicate a nonlinear relationship. Log-log plots of PI vs five-micron clay content show that the PI varies directly with the square of the clay content. The other mathematical relationships are indicated in the figure.

Since these loess data exhibit such a good correlation, irrespective of source, it is concluded that the mineralogy is quite uniform and that the Atterberg limits are primarily dependent upon the amount of clay present. It also might be intuitively reasoned that other properties would follow a similar relationship and that loess of similar gradation would exhibit similar disturbed properties regardless of location.

PERMEABILITY

The only published permeability data available were found in the Holtz and Gibbs paper (10), which indicates a wide variation in permeability of the loess in Nebraska, Iowa, Kansas, and Colorado. The data were obtained as a part of consolidation testing

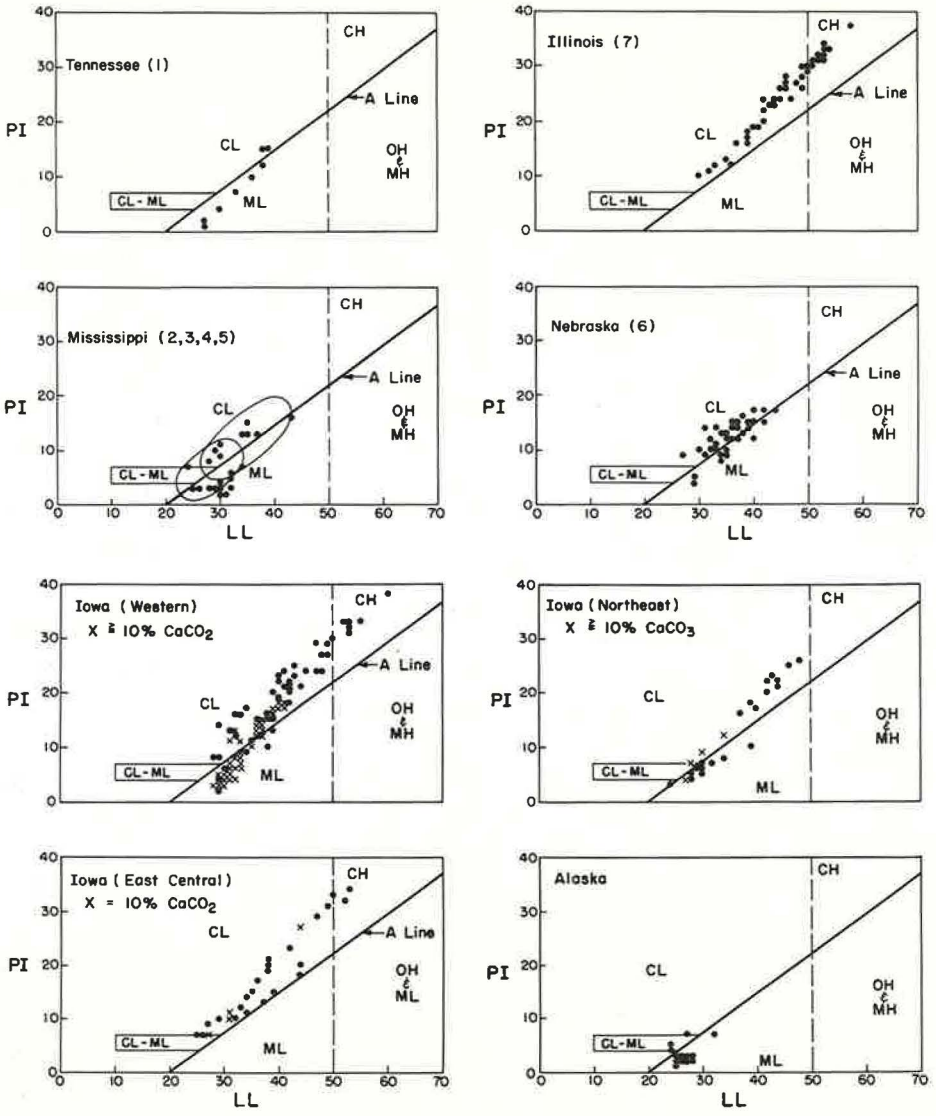

Figure 2. Plasticity data of loess in the United States.

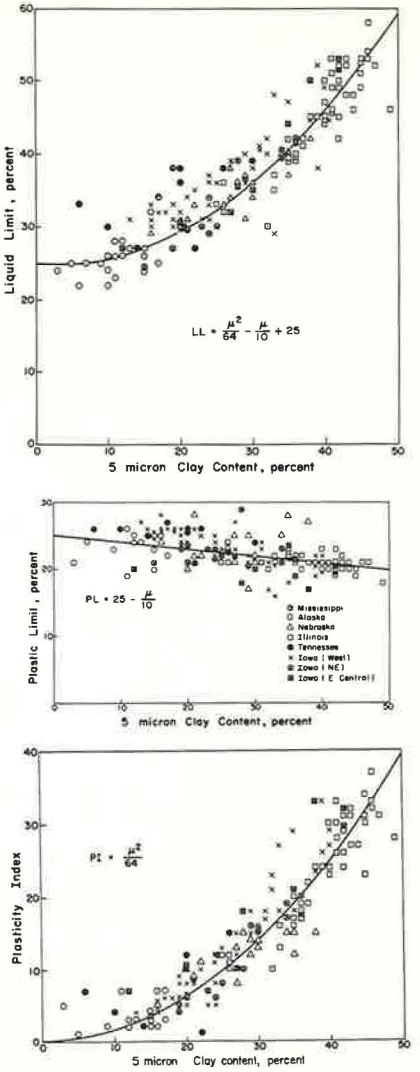

Figure 3. Plasticity data as a function of five-micron clay content for loess in the United States. The symbol μ represents five-micron clay content in the equations.

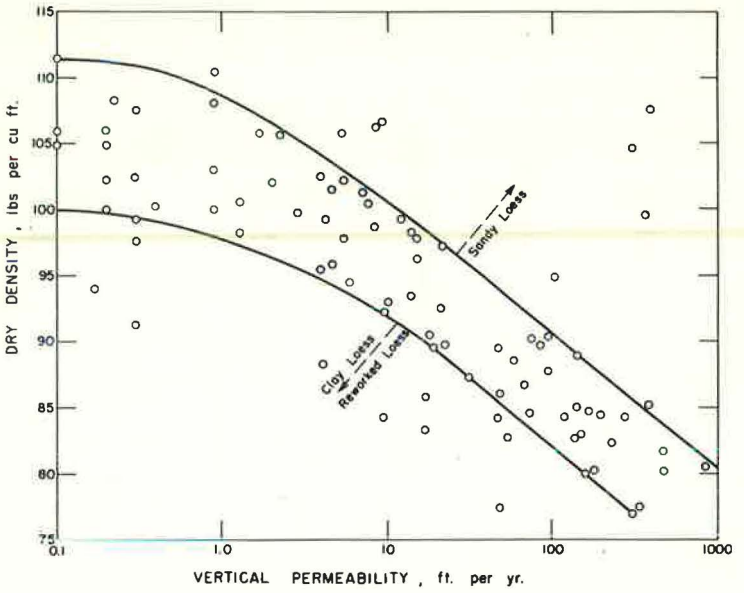

Figure 4. Vertical permeability data from consolidation tests on loess in the Missouri River Basin, from Holtz and Gibbs (10).

of samples from nine different sites for earth dams. All values of permeability were determined after consolidation was complete under a given load. The data at low densities represent tests completed with small loads and, hence, give values of permeability nearest to those to be expected of undisturbed samples. Therefore, the in-place vertical permeability of loess should be expected to be in the range of 10 to over 1,000 ft per year. The data are shown in Figure 4.

Terzaghi (21) describes the permeability of loess as a very elusive property. He bases this observation on the breakdown of the loess structure on saturation that is accompanied by densification and a consequent change in permeability.

DENSITY

The in-place dry density of loess in the United States varies from 66 to 104 pcf. Studies in Iowa (6) indicate that the in-place density is dependent on the depth (or loess overburden) and on the clay content. Depth studies to 90 ft indicate some variance of density at shallow depths, approximately consistent with clay content, to a gradual nearly linear increase of density with a depth below 10 to 20 ft. Values ranged from 66 to 99 pcf.

Standard density tests values for United States loess range from 100 to 112 pcf and optimum moisture contents from 13 to 20 percent. Modified density test results vary from 113 to 119 pcf with optimum moisture values between 13 to 18 percent.

SHEAR STRENGTH

The values of the constants of the Coulomb empirical shear strength equation reported in the literature vary considerably. The variance is largely due to the moisture conditions at the time of testing. Density and texture also exert some influence on these properties.

The angle of internal friction reported fell between 28 and 36 deg for samples tested with moisture contents below saturation. Samples that were tested at low density and near saturated moisture conditions gave internal friction angles of zero or near zero at low normal stresses.

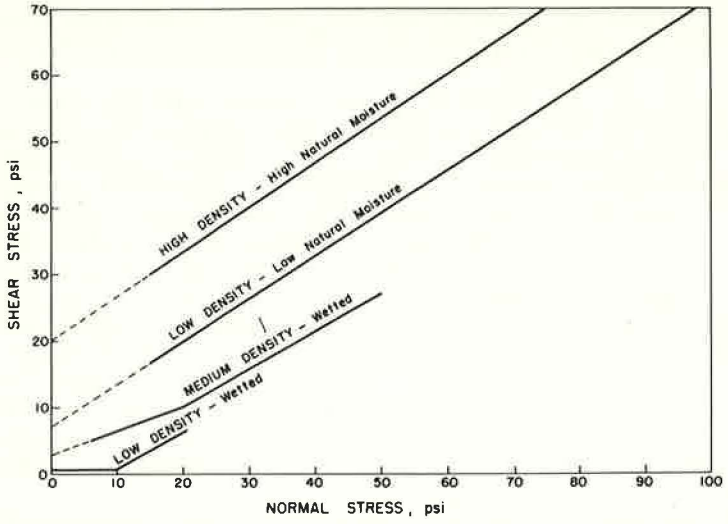

Figure 5. Typical shear envelopes for loess in the Missouri River Basin, from Clevenger (5).

The values of cohesion reported vary from zero to near 70 psi, depending on the initial density, initial moisture content, and the clay content of the loess. High values of cohesion result from high density, low moisture content, and high clay content. The highest values of cohesion stem from very low moisture samples that are extremely clayey and dense.

Typical shear strength envelopes for loess as reported by Clevenger (5) are shown in Figure 5. These envelopes agree very well with those reported by Holtz and Gibbs (10), which also indicate that the greater the clay content of the loess the greater the value of cohesion, all other factors remaining constant. Holtz and Gibbs also present curves showing the effects of drained shear, sealed shear, wetting, natural density, and preconsolidation on the shear strength constants of loess. These variables are primarily reflected by changes in cohesion.

CONSOLIDATION

Holtz and Gibbs (10) consider the susceptibility of loess to high degrees of consolidation to be its outstanding physical and structural property. This observation is also

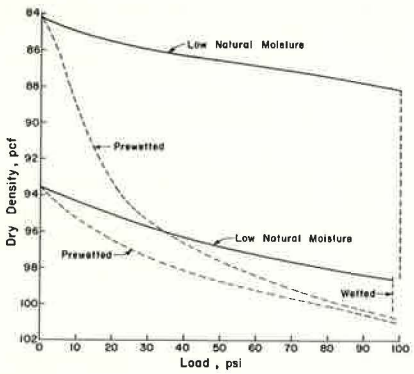

Figure 6. Typical consolidation curves for loess in the Missouri River Basin, from Clevenger (5).

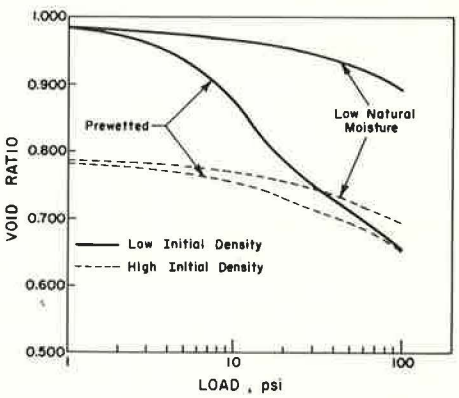

Figure 7. e-log p curves (from data in Fig. 6).

supported by Clevenger (5). Karl Terzaghi (21) describes loess as among the most treacherous of foundation soils because of the breakdown of its structure following saturation.

Holtz and Gibbs (10), in a series of research tests, found that loess consolidates to densities that are only slightly smaller than the densities obtained in standard compaction tests. Their results also show that wetting causes a sudden collapse of the structure accompanied by considerable consolidation, the amount depending on the initial density. The density resulting from wetting was found to be the same regardless of whether the material was wetted prior to loading or after the load was applied (Fig 6). These curves can be used to calculate the approximate effect of saturation on consolidation of loess at different initial densities. The data are also shown in Figure 7 in the conventional manner of void ratio vs the logarithm of loading pressure. The compression index for three of these curves has not been calculated because of the absence of a clearly linear section on the curves. For the saturated low initial density curve, the compression index is 0. 180. Void ratio-log p curves of data from Holtz and Gibbs (10) give values of the compression index of 0. 27 for a sample containing natural moisture and 0. 33 for a saturated sample. Krinitzsky and Turnbull (13) report values ranging from 0. 09 to 0. 23 for Mississippi loess.

The differences in the density-load relationships at different moisture conditions provide an essential clue to the structural behavior of the material. The dependence of preservation of structure, when loaded, on the cementation of the skeletal structure of the loess is clearly demonstrated. Wetting is much more effective in causing a collapse of the structure than loading. Wetting causes the clay bond to soften, which allows the structural collapse.

BEARING CAPACITY

Studies by the Bureau of Reclamation have indicated that the density of loess is the most outstanding characteristic by which settlements can be predicted. Laboratory experiments show that the probability for large settlements is small if the initial density is greater than 90 pcf.

Plate bearing tests reported by Holtz and Gibbs (10) and Clevenger (5) indicate that the bearing capacity of dry loess may exceed 5 tons per square foot and may drop to 0. 25 tons per square foot when wetted. The variance of density and moisture content, even within limited areas, necessitates investigations at each site of major importance.

NATURAL MOISTURE CONTENT

The natural moisture content (field moisture) of loess varies from 4 to 49 percent. Peck and Ireland (17) have found a correlation between field moisture content and the average annual rainfall at the location of the loess. They concluded that the behavior of loess in humid regions should be expected to differ from that in semiarid regions.

Krinitzsky and Turnbull (13) state that the infiltration rates of rainfall into loess preclude the possibility of the loess becoming saturated, except where there is a water table. Loess may often remain permanently dry only a few feet below the surface.

EROSION

Loess in its natural state offers very little resistance to erosion by flowing water. No engineering test or criterion exists to measure this property but its importance cannot be stressed enough. Numerous examples are on record of great erosion gullies (some might be termed canyons) developing in a matter of weeks or even days.

SUMMARY

A summary of the ranges in values of the engineering properties of loess in the United States is given in Table 1. These values were taken from the literature sources cited below the locations. Generally, there is not much difference in the ranges of the properties from state to state.

TABLE 1

RANGE IN VALUES OF ENGINEERING PROPERTIES OF LOESS IN THE U.S.

Property	Location and Reference							
	Iowa (11, 15)	Nebraska (3, 10)	Tennessee (18)	Mississippi (12, 13, 22, 23)	Illinois (14)	Alaska (2)	Washington (4)	Colorado (5)
Specific gravity	2.68-2.72	2.57-2.69	2.65-2.70	2.66-2.73		2.67-2.79		
Mechanical analysis								
Sand, percent	0-27	0-41	1-12	0-8	1-4	2-21	2-10	30
Silt, percent	56-85	30-71	68-94	75-85	48-64	65-93	60-90	50
Clay, percent	12-42	11-49	4-30	0-25	35-49	3-20	8-20	20
Atterberg limits								
LL, percent	24-53	24-52	27-39	23-43	39-58	22-32	16-30	37
PL, percent	17-29	17-28	23-26	17-29	18-22	19-26		20
PI	3-34	1-24	1-15	2-20	17-37	NP-8	<8	17
Classification								
Textural	SL, SCL, SC	SL, SCL, SC	SL, SCL, SC	SL, SCL	SC, C	SL, SCL		SL
AASHO	A-4(8) A-7-6(19)	A-4 A-6	A-4(8) A-6(10)	A-4(8) A-6(9)	A-6(11) A-7-6(20)	A-4(8)		A-6(10)
Unified	ML, CL, CH	ML, CL	ML, CL	ML, CL	CL, CH	ML, CL-ML		CL
Density test data								
Standard OM, percent	15-20		14-16			13-18		
Modified OM, percent	13-18							
Standard MD, pcf	103-112		100-108			103-112		
Modified MD, pcf	113-119							
In-place MD, pcf	66-99			80-104				76-95
Field moisture, percent	4-31		12-25	19-38		11-49		8-10
Shear strength								
Unconfined compression test				2-8				
Unconsolidated undrained triaxial shear,								
c, psi		0-67		2-10				
ϕ		31-36°		0-28°				
Consolidated undrained triaxial shear,								
c, psi	0-8			3-8				
ϕ	28-31°			26°				
Consolidated drained direct shear,								
c, psi	0.3-1.8			0				
ϕ	24-25			32-33°				
CBR				10-13				

It is interesting to note that authors entertain somewhat different opinions concerning whether or not loess varies significantly in its properties. Terzaghi (21) states, "By comparing his data [referring to Scheidig (19)] concerning the consolidation characteristics, permeability and effects of saturation with those described in the paper under consideration [Holtz and Gibbs (10)] one realizes that the properties of loess are international. There is not even a significant difference between the typical desert loess of Central Asia and the loess in the Mississippi Valley which derived its material from the valley trains of Pleistocene meltwater streams."

Krinitzsky and Turnbull (13) state, "The properties of Mississippi loess are essentially the same as those of loess in major deposits elsewhere in the world. Reference to the now classic work by Scheidig [19], in which data are presented on loess deposits in such widespread areas as China, Soviet Union, Central Europe, Argentina, and Central and Midwestern United States, shows that there are remarkable similarities in the loess deposits everywhere."

Contrast the above thoughts with those of Peck and Ireland (17), i.e., "The writers have come to regard loess not as a soil of remarkably constant and uniform properties, but as one possessing local and regional variations almost as striking as those of some glacial materials."

These statements, on the surface, seem to be at odds. However, it is the opinion of this author that they are compatible and the primary difference lies in the perspective with which one views the properties of loess. No doubt Terzaghi et al were viewing the problem by qualitatively comparing the behavior of loesses of similar texture. Peck and Ireland quantitatively compare the behavior of loesses of different texture.

Certainly the behavior of a loess having a low clay content and a high carbonate content could not be expected to behave to the same degree as a loess that is high in clay content and low in carbonate content. However, the behavior characteristics are similar in that they both have the ability to stand in vertical cuts and both consolidate considerably when saturated.

The following are conclusions regarding loess on which most authors agree:

1. Loess is a soil of predominately silt size with small amounts of sand.
2. The physical characteristics of gradation, compaction, Atterberg limits, and classification are very uniform.

3. The structure is open and porous.
4. Bonding is primarily due to thin clay coatings.
5. In-place densities range from 66 to 104 pcf.
6. Large settlements are uncommon for in-place densities of over 90 pcf.
7. Natural moisture contents are generally well below saturation and range from 4 to 49 percent.
8. Bearing capacity depends primarily on the in-place density.
9. Consolidation proceeds rapidly under load when loess is saturated or near saturation.
10. Shearing strength is greatly dependent on moisture content.

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance provided by the Engineering Research Institute, Iowa State University.

REFERENCES

1. Akiyama, F. M. Shear Strength Properties of Western Iowa Loess. Unpublished MS thesis, Iowa State Univ., 1964.
2. Alaska Department of Highways. Private communication, 1965.
3. Bollen, R. E. Characteristics and Uses of Loess in Highway Construction. Am. Jour. of Sci., Vol. 243, May 1945.
4. Cedergren, H. R. Discussion of "Experiences With Loess as a Foundation Material." Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 83, No. 1155, pp. 19-21, 1957.
5. Clevenger, W. A. Experiences with Loess as a Foundation Material. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 82, No. 1025, pp. 1-26, 1956.
6. Davidson, D. T., and Associates. Geologic and Engineering Properties of Pleistocene Materials in Iowa. Iowa State Univ. Eng. Exp. Sta. Bull. 191, 1960.
7. Davidson, D. T., Roy, C. J., and Associates. The Geology and Engineering Characteristics of Some Alaskan Soils. Iowa State Univ. Eng. Exp. Sta. Bull. 186, p. 67, 1959.
8. Davidson, D. T., and Sheeler, J. B. Cation Exchange Capacity of Loess and Its Relation to Engineering Properties. ASTM Spec. Tech. Publ. No. 142. pp. 1-19, 1952.
9. Davidson, D. T., and Sheeler, J. B. Clay Fraction in Engineering Soils: III. Influence of Amount on Properties. HRB Proc., Vol. 31, pp. 558-563, 1952.
10. Holtz, W. G., and Gibbs, H. J. Consolidation and Related Properties of Loessial Soils. ASTM Spec. Tech. Publ. No. 126 pp. 9-26, 1951.
11. Iowa State Univ. Eng. Exp. Sta. Soil Research Lab., Data Files, 1965.
12. Kolb, Charles R. Physical Properties and Engineering Characteristics of Mississippi Loess. Unpublished research, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1965.
13. Krinitzsky, E. L., and Turnbull, W. J. Loess Deposits of Mississippi. Unpublished research, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1965.
14. Liu, T. K., and Thornburn, T. H. Engineering Index Properties of Some Surficial Soils in Illinois. University of Illinois Eng. Exp. Sta. Bull. 477, 1965.
15. Olson, G. R. Direct Shear and Consolidation Tests of Undisturbed Loess. Unpublished MS thesis, Iowa State Univ., 1958.
16. Peck, O. K., and Peck, R. B. Settlement of Foundation Due to Saturation of Loess Subsoil. Proc. Second Internat. Conf. on Soil Mech. and Found. Eng., Vol. IV, pp. 4-5, 1948.
17. Peck, R. B., and Ireland, H. O. Discussion of "Experiences With Loess as a Foundation Material." Jour. of the Soil Mech. and Found. Div., Proc. ASCE, Vol. 83, No. 1155, pp. 21-34, 1957.
18. Royster, David L. Engineering Characteristics of Loessial Soils in Western Tennessee. 45th Annual Tennessee Highway Conference, 1963.

19. Scheidig, A. Der Loess. Theodor Steinkopff, Dresden, Germany, 1934.
20. Sheeler, J.B., and Davidson, D. T. Further Correlation of Consistency Limits of Iowa Loess With Clay Content. Proc. Iowa Acad. Sci., Vol. 64, pp. 407-412, 1957.
21. Terzaghi, Karl. Discussion of "Consolidation and Related Properties of Loessial Soils." ASTM Spec. Tech. Publ. No. 126, pp. 30-32, 1951.
22. Turnbull, W. J. Field and Laboratory Investigation for Blast-Load Simulator Foundation. Unpublished report, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1965.
23. Turnbull, W. J. Foundation Investigation for proposed Administration and Technical Services Building. Unpublished report, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1965.