PORE STRUCTURE OF FRIABLE LOESS

W. W. Badger, U.S. Army Corps of Engineers; and
R. A. Lohnes, Iowa State University

•THE SIZE, shape, and arrangement of mineral grains composing a soil mass, referred to as structure, have profound influence on the engineering behavior of soil. Many soil mechanicians have recognized the relation of structure to soil shear strength as exemplified by Henkel (6) who, in discussing clay strength, stated: "Some model for the clay structure has to be found which will enable the deformations and pore pressures to be related in a consistent and satisfactory manner."

Other engineering aspects of soil structure involve sensitive soils, compressibility, and permeability. The loss of strength between the undisturbed and the remolded states in sensitive soils is explained as a difference in structure because the density is the same in both cases. The void ratio log pressure curves resulting from confined compression tests on sensitive soils are very flat in the low-pressure range but drop precipitously in the high-pressure range, which has been interpreted as the collapse of soil structure when a critical pressure is reached. At low densities, loess has considerable variation in permeability for a constant density or void ratio as shown by Badger (2). Although a portion of that scatter is due to experimental error, additional scatter is explained as the result of structural differences.

Two serious limitations arise in a study of soil mechanics and structure: One is that the structure is ill-defined, and the other is that soil structure lacks adequate quantification. This paper addresses those 2 general problems and provides some descriptive data for friable loess. A fabric factor has been developed that provides a concept that may contribute to a quantitative classification of soil structure.

DEFINITIONS OF SOIL STRUCTURE

Jenny (9) pointed out that there is no generally accepted definition of soil and that a definition that would satisfy all soil workers is practically impossible to find. The problems inherent in defining soil structure are basically the same as those encountered in defining soils. With the varying interest of geologists, pedologists, and engineers studying soil structure, it is no wonder that there are so many different definitions.

Three terms occur in descriptions of size, shape, and arrangement of soil particles. Structure, fabric, and texture are sometimes used as synonyms but more often have differences in meaning. Various points of view regarding that terminology can be found in the Soil Survey Manual of the U.S. Department of Agriculture (19), the glossary of geological terms published by the American Geological Institute (1), and textbooks on soil physics (3, 4) and on soil mechanics (18).

There is also little agreement on what a particle is or on how particles go together. Therefore, the following definitions, which are close to those of Brewer (4), will be used in this paper:

1. Sand grains, silt grains, and clay crystals are considered as primary soil particles;
2. A composite particle is composed of primary particles that are joined together by some cohesive force;
3. Soil structure is the size, shape, and arrangement of primary or composite particles or both;

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4. Fabric is one aspect of structure that describes a specific arrangement involving elements such as lineations; and
5. Texture is a qualitative term for describing particle size (e.g., sand or clay) and is another aspect of structure.

Techniques for measuring and quantitatively describing texture are well known. Similarly techniques for measuring particle shape such as sphericity and roundness are common to petrologists although not often used by soil engineers. Void ratio and porosity, in a sense, are measures of structure or fabric in that they quantitatively describe the void volume in the soil mass. However, if a given void volume is distributed as a few large pores rather than many small ones, the engineering behavior of the soil will differ. Those considerations suggest that measures of pore-size distribution should be helpful in quantifying soil fabric.

PORE-SIZE DISTRIBUTION

Some engineers (12, 16) have used thin sections and light microscopy for soil-structure studies in conjunction with soil mechanics. Lafeber (11) suggested using petrographic techniques such as equal-area spherical projections as a means of quantifying soil fabric. Unfortunately, many undisturbed soils do not possess the lineations of particles or voids that make this technique so successful in petrography.

A significant advance in soil-structure studies was made by Diamond and his associates who demonstrated that mercury-injection porosimetry can be used to characterize the pore-size distribution of soils and to provide a better understanding of engineering modifications of soil such as compaction (5, 17).

That technique is based on the Washburn (20) equation, which gives the pressure required to force mercury into capillary pores.

$$P = \frac{-2\ T \cos \theta}{r}$$

where P is pressure, T is surface tension, θ is angle of contact, and r is radius of pore. After oven-drying and weighing, the sample is placed in the mercury-injection chamber where a vacuum pump removes the pore gases. Although oven-drying of most soils results in shrinkage, which may alter the pore-size distribution, the shrinkage of friable loess due to oven-drying is less than 1 percent by volume. Then the chamber is filled with mercury, and at increments of pressures the volume of mercury intruded into the pores is measured. From the pressures obtained, pore size and volumes may be determined (15). Purcell (13) used an apparatus to determine mercury capillary pressures as high as 2,000 lb/in.^{2}, which filled all accessible pores with radii larger than 5.3×10^{-6} cm (533 Å); that apparatus is similar to the equipment used in this study. Winslow and Shapiro's (21) hydraulic mercury-intrusion porosimeter was capable of pressures of 3,000 lb/in.^{2}. Diamond (5) used a modified Aminco-Winslow porosimeter that has a measuring capacity of 15,000 lb/in.^{2} and can measure pore radii down to 7.11×10^{-7} cm (71 Å).

Both Diamond (5) and Sridharan et al. (17) point out the limitations of the mercury-injection technique and the relation of mercury injection to capillary condensation, which measures void size distributions from 16 to 200 Å. The size distribution of those very small pores has important ramifications in terms of the surface chemistry and physicochemical behavior of clays; however, when gross engineering behavior of soils is studied, such as compaction, deformation, or permeability, those pores are probably not so important, for they reflect the intraparticulate behavior rather more than interparticulate behavior.

In this study of friable loess, 86 percent by weight of the particles are silt size or larger, so the comparatively low-pressure mercury-injection apparatus used here was considered adequate. Huang and Demirel (8) in a companion study used the capillary condensation technique to provide some fundamental data on the very small pore distribution in an undisturbed sample of friable loess.

The soil used in this research was loess obtained from Prospect Hill in Sioux City, Iowa, near the intersection of Bluff and Prospect streets on a large bluff adjacent to the Missouri River floodplain. The physical properties of the loess are given in Table 1. It is a silty loess according to the classification by Holtz and Gibbs (7) or a friable loess when considered in terms of relative plasticity.

Undisturbed samples were obtained by forcing thin-walled steel Shelby tubes into the soil by the use of hydraulic jacks and by hand-carving soil from the face of the bluff. Samples were collected at depths of about 4 ft below the surface.

The remolded samples were statically compacted in a cylindrical mold ½ in. in diameter and 1 in. in length. The soil was weighed to give a predetermined density and then statically compressed to the standard volume. Samples were similarly molded to Harvard miniature size for permeability and unconfined compression tests.

The mercury-injection apparatus is composed of essentially 3 components: the mercury displacement pump, the sample chamber, and the pressure manifold system (Fig. 1). Purcell (13) gives a more detailed treatment of the type of porosimeter used in this study.

The oven-dried specimen was placed in the porosimeter chamber where a vacuum of 30 μm was obtained. Twenty minutes is usually required to remove most of the entrapped air and moisture from the loess sample.

Mercury was introduced into the chamber so that it completely surrounded the specimen. When the mercury level reached the upper reference mark and the chamber was under 30-μm pressure, the 0-psia reading was taken. At that point the vacuum pump was stopped, and 5 psia of nitrogen was applied to the mercury in the chamber. At predetermined pressure increments, the nitrogen forced the mercury into the loess sample; and the volume of mercury forced into the specimen was recorded at each increment of pressure up to 2,000 psia.

When the loess sample was removed, each specimen was visually inspected. In no case was any sample crushed or damaged; however, the sample shrunk 0.8 percent by volume, and each sample appeared to be completely saturated with mercury when broken apart.

The loess specimens were weighed before and after drying to determine the molding moisture. The remolded cylindrical specimens were measured, and the total volume was calculated. The dry weight and total volume were used to determine a dry density for each specimen.

The total volume of the specimens could be determined by subtracting the volume of mercury introduced into the chamber with the sample in it from the total volume of the chamber at a pressure of 0 psia. However, because of possible errors due to a minute amount of dissolved air in the mercury, that method of total volume measurement was discarded in favor of measuring the gross geometry of the samples. From that volume and the dry weight of the samples, the void ratio was computed. Prior to their placement in the porosimeter, the pieces that were broken from the larger samples were weighed, and the volume of solids was computed by the use of the specific gravity of 2.7. The void volume of the small piece was computed from void ratio and volume of solids.

The mercury volumes measured at the different pressures were corrected for mercury compressibility. The 2,000-psia pressure was used as the upper limit in most tests; however, a few tests were conducted at 1,600 and 1,800 psia. The pressures were converted to radius of pores by use of the Washburn equation, and the data were plotted as pore volume intruded per unit weight versus pore diameter. Cumulative curves were generated by dividing the volume of mercury injected into the sample per pressure-radius increments by the total void volume and then multiplying by 100 to obtain percentage of void volume per total void volume.

The selection of a contact angle and surface tension value was made after an extensive literature search (14, 13, 21, 10, 5, 17). The values of 140 deg and 480 dynes/cm appear reasonable values for minerals in loess. Oven-drying at 105 C for days prior to pumping and waiting 20 min for the pumping down of the 30-μm vacuum removed most of the moisture and air from the sample. A correction for the kinetic hysteresis effect was made by allowing the mercury level to stabilize before a reading was taken.

Figure 2 shows the total porosity of loess as calculated from the known weights of soil, volume of the cylindrical mold, and specific gravity of 2.7 and as measured by mercury injection. The 45-deg line represents the line that would indicate complete agreement between the 2 measurements of porosity. The curve demonstrates that at porosities between 0.3 and 0.45 approximately 10 percent of the pore volume is not intruded by the mercury. At porosities of about 0.55, there is a deviation of nearly 30 percent between the 2 porosity calculations.

Mercury-injection tests on undisturbed samples of loess at porosity of 0.494 revealed that from 17 to 22 percent of the available void volume was not intruded by mercury. Huang and Demirel (8) measured the pore-size distribution in an undisturbed loess sample using the sorption isotherm method and found that the pores with diameters less than about 0.1 μm (i.e., below the size range of the mercury porosimeter) constitute 20 percent of the total pore volume. The interpretation is that at the lower porosities about 10 percent of the pores are too small to be intruded by the mercury. At higher porosities, the greater deviation is accounted for in part by the movement of mercury into large voids on the surface of the soil cylinder at 0 psia. As the mercury tends to partially fill those large surface irregularities, both the measured total volume and the void volume are reduced the same amount so that the total porosity is reduced. That deviation may also be due to a limitation in the Washburn equation at that void size.

The comparison of the pore distribution of undisturbed loess and of remolded loess at the same densities is shown in Figure 3. Each curve represents the average of 3 tests and reveals a rearrangement of pore-volume distribution caused by remolding. Remolding eliminated a portion of the larger pores and increased the maximum pore volume peak of the loess from 13 to 20 percent in volume and the pore radius from 2.7×10^{-4} to 5.3×10^{-4}. In general, the undisturbed loess has a more uniform distribution of pore volume. Some engineering implications of the redistribution of voids caused by remolding are a higher permeability and a greater compressibility in the undisturbed loess.

Twelve loess samples were statically compacted in the ½-in. diameter molds to void ratios ranging from 0.427 to 1.431. The 5 curves shown in Figure 4 are representative of the results of all the tests. All samples were compacted with 16 percent moisture content, which is near optimum for standard Proctor density. The pattern shown in Figure 4 is similar to the results of Sridharan et al. (17) in which the voids are eliminated in order of largest to smallest as the density of remolded loess is increased. That is reasonable because the larger voids formed by the arching of individual grains would be the weakest structural link of the soil system. That is seen from elementary considerations of the larger moments developed in larger arches. For a high-density range, the remolded loess samples disclose relatively few differences in void distributions to density changes. In the low-density range, a small change in density generates a relatively large void distribution change.

SOIL FABRIC FACTOR

A common method of describing a soil for engineering purposes is the grain-size distribution curve obtained from sieve and hydrometer analyses. These data compared to cumulative void-size distribution data provide a means to quantitatively describe the soil structure. By converting the amount of mercury injected into the voids to equivalent diameters, accumulating the volume filled, and computing that as a percentage of the total void volume, one can compare the void-size distribution curve to the grain-size distribution curve computed on a volumetric basis (Fig. 5). To convert the grain-size curve from a weight basis to a volume basis requires the assumption that the specific gravity of the loess particles is constant in all size ranges. That assumption probably does not hold in the clay-size range, and the lower portion of the grain-size curve should shift. However, the upper portion and center of the curve will probably move very little. Further, the assumption that cylindrical pores and void-ratio calculations are based on constant solid density introduces some deviations in pore-size distribution. All distributions are relative to assumptions.

Table 1. Properties of friable loess.

Property	Amount
Grain size distribution, percent by weight	
Clay (< 0.002 mm)	14
Silt (0.002 to 0.074 mm)	86
Specific gravity	2.7
Undisturbed dry density, lb/ft^3	85.3
Liquid limit, percent	30
Plastic limit, percent	26
Standard Proctor compaction	
Optimum moisture content, percent	16.5
Maximum dry density, lb/ft^3	109.4
Field moisture content, percent	7 to 10
Drained triaxial strength (at 85.3 lb/ft^3)	
Cohesion, $lb/in.^2$	1.0
Internal friction angle, deg	32.2
Mineralogy	Quartz, calcite, dolomite, feldspar, montmorillonite, and illite

Figure 1. Shell mercury porosimeter.

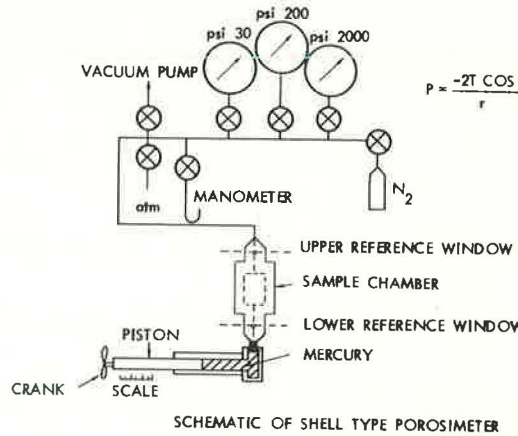


Figure 2. Relation between porosity calculated from bulk density and porosity calculated by mercury injection.

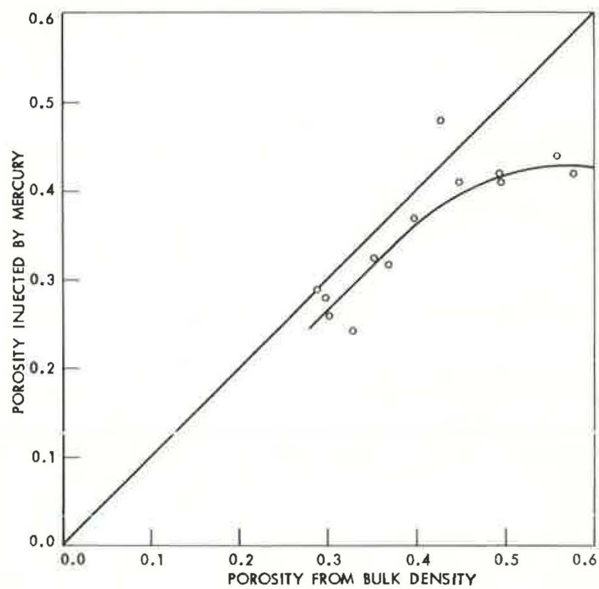


Figure 3. Pore-size distribution of undisturbed loess and loess remolded to field density.

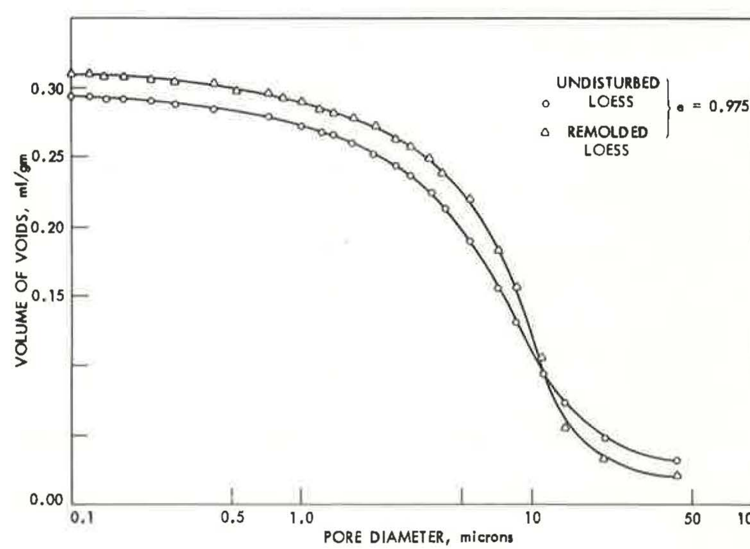


Figure 4. Pore-size distribution of loess compacted to various densities.

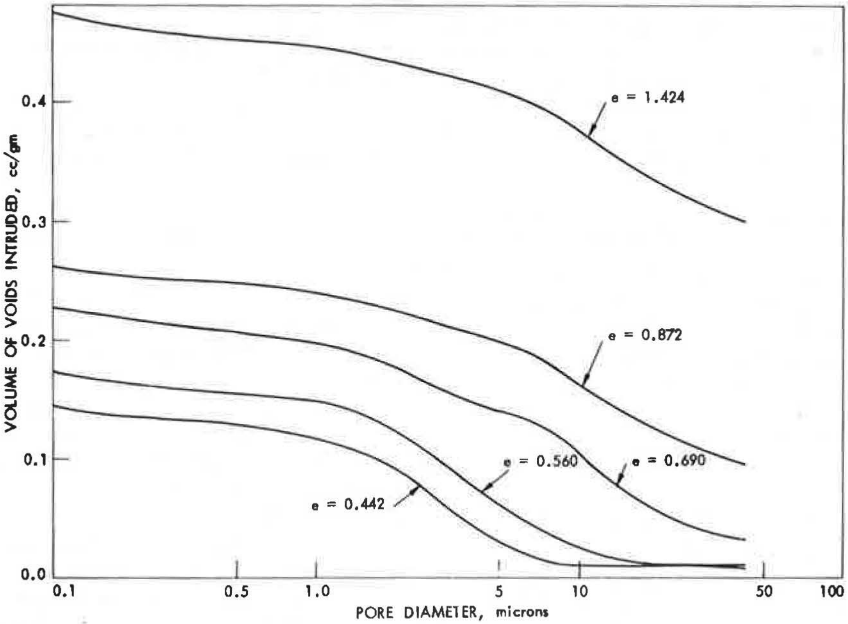


Figure 5. Cumulative pore-size and grain-size distribution as boundaries between various structural classes.

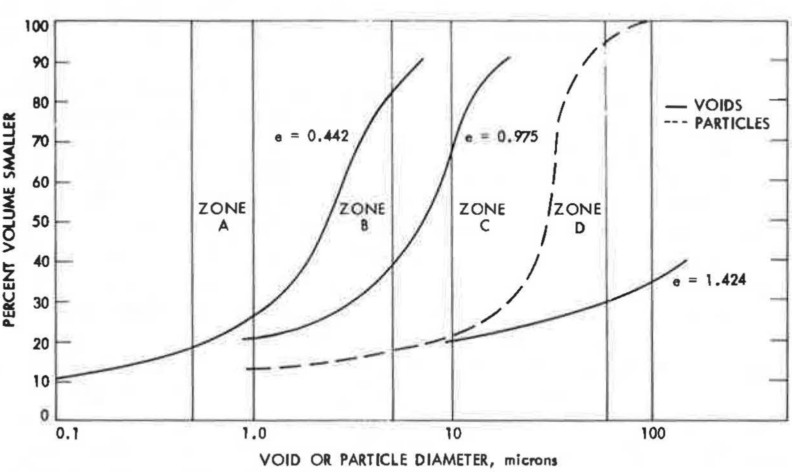


Figure 5 shows the void-size distribution curves for remolded and undisturbed loess plotted with the grain-size distribution curve for loess. At the far left is the void-distribution curve for loess compacted to maximum density at optimum moisture content. The similarity of shapes of the 3 curves is clear and suggests that particle size and shape have a significant influence on the size of the voids.

A conceptual approach to describe soil structure is to use the distribution curves shown in Figure 5 as boundaries for zones. The boundaries are based on observation of loess structure with the scanning electron microscope; micrographs are shown in Figure 6.

The first boundary is the void-size distribution curve for maximum density, the second boundary is the void-size distribution curve for undisturbed loess, and the third boundary is the grain-size distribution curve for loess.

Zone A represents an area above the maximum laboratory density for loess. To attempt higher densities will probably cause crushing of primary particles. Any pore-size distribution curve falling in this zone will be classed as an altered particle structure. No attempts were made to compact loess to that degree.

Zone B represents an area of relatively dense loess (normally higher than the undisturbed or field density) in which primary particles are in contact with each other. Any pore-size distribution curve falling in zone B is designated a particulate structure. The structure shown in Figure 6a is representative of that type of structure.

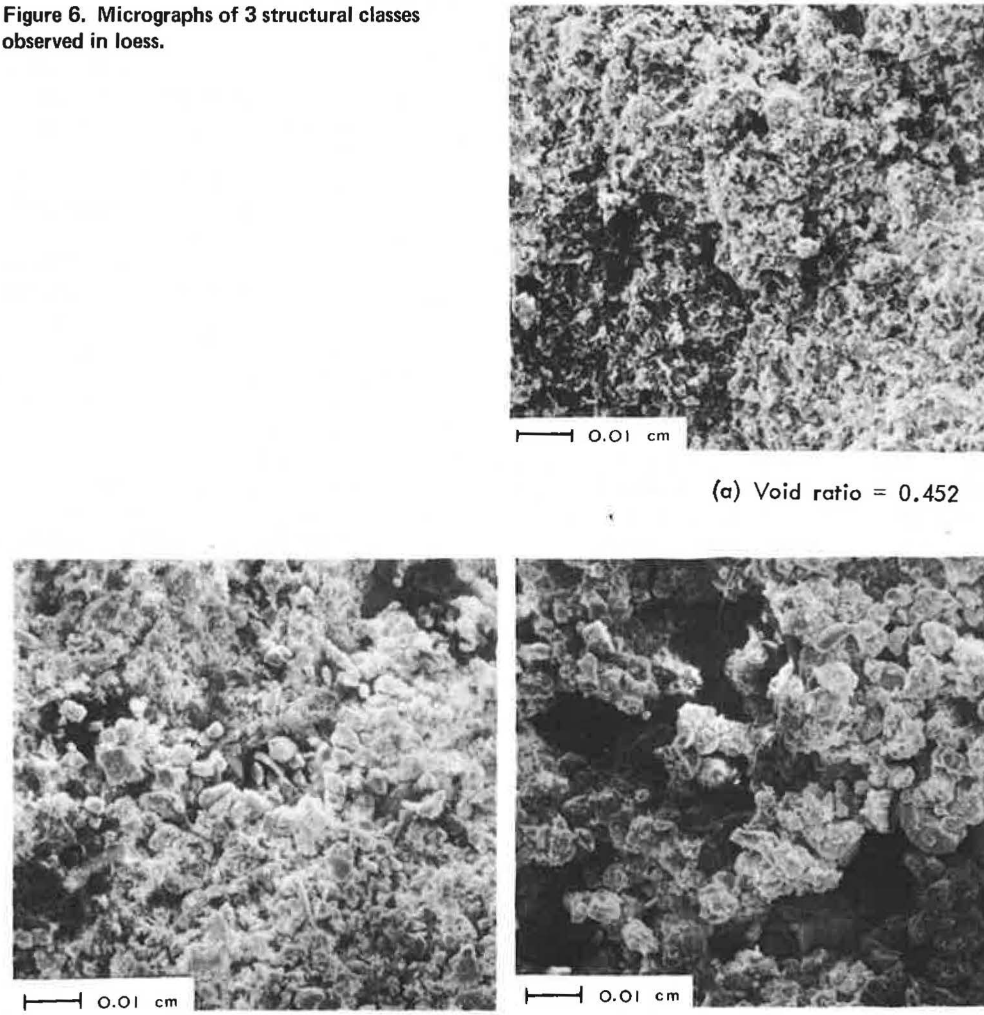
Zone C represents an area in which many of the primary particles are joined together to form composite particles and 2 classes of voids: the composite void formed among composite particles and the particulate void formed among primary particles. The large composite voids characterize the structure in this zone as shown in Figure 6b. Any pore-size distribution curve falling in that zone is called a composite structure.

Zone D represents the loosest structure where the dominant voids are larger than their adjacent grains and are formed by bridging and arching of composite particles. Figure 6c shows that type of structure. Any void-size distribution curve falling in that area is called a honeycomb structure. Both the altered particle and honeycomb structure classes are more theoretical or limiting structures and will probably rarely occur in loess.

Although the structural zones can be differentiated, a parameter is needed to quantify the structure. A grain-size to void-size ratio at 50 percent fines is defined as the fabric factor. For example, at 50 percent fines on the void-size distribution curve for undisturbed loess, the void diameter is 0.00058 cm. On the grain-size distribution curve, the grain size at 50 percent fines is 0.0031 cm. By dividing the grain diameter of 0.0031 cm by the void diameter of 0.00062 cm, one obtains the fabric factor of 5.43.

Table 2 gives some representative fabric factors for loess and for the soils studied by Diamond and his associates. All of the compacted soils have fabric factors that are greater than one except for the very low-density loess and artificially sedimented kaolinite. It is reasonable, especially in the latter case, that those 2 soils would exhibit a looser structure than soils that have been compacted. A comparison of compacted loess and compacted kaolinite at a void ratio of 0.59 indicates that the fabric factor of the kaolinite is $1\frac{1}{2}$ times larger than that loess. Illite at void ratio of 0.57, on the other hand, has a fabric factor approximately one-third as large as the loess. Undisturbed loess at a void ratio of 0.975 has a fabric factor 20 percent greater than that of compacted loess at the same void ratio. Those comparisons indicate that the fabric factor is sensitive to structural differences in soils and that void ratio alone is unable to measure the difference. Fabric factor systematically decreases as void ratio increases except for the 2 anomolous values at void ratio of 0.975. It should be remembered that the remolded sample was compacted at 10 percent moisture content, whereas the other samples were compacted near optimum moisture content, suggesting that molding moisture also influences structure. For both compacted kaolinite and compacted loess, there is an increase in fabric factor with decreasing void ratio as shown in Figure 7.

Figure 6. Micrographs of 3 structural classes observed in loess.

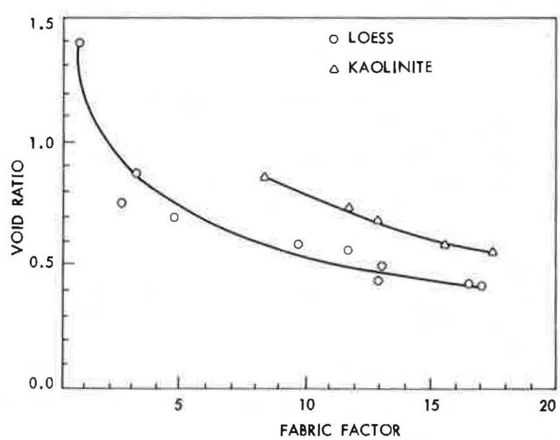


(a) Void ratio = 0.452

(b) Void ratio = 0.975

(c) Void ratio = 1.217

Figure 7. Relation between void ratio and fabric factor for loess and kaolinite.



SUMMARY AND CONCLUSIONS

The mercury-injection technique can be used to describe the pore-size distribution of friable loess in both undisturbed and compacted states. The pore-size distribution of samples compacted to essentially the same void ratio as the field condition shows fewer large-sized pores and, in general, a more uniform distribution of pore sizes than the undisturbed samples. Loess samples compacted to various densities at optimum moisture content show trends similar to those observed by Sridharan et al. (17) in that there is a decrease in mean pore size with increasing compaction and that the major reduction in pore volume is achieved by reducing the larger pores.

A comparison of scanning electron micrographs and curves of pore-size distribution plotted on a percentage smaller basis and curves of grain-size distribution reveals that various types of loess structures can be classified. The 3 prevalent structures in loess are the particulate in which primary grains are in contact and the voids are in general much smaller than the grains, the composite in which the primary grains are aggregated into secondary clusters and the sizes of few voids are larger than the grains, and the honeycomb in which the grains form arches over many large voids.

Void ratio and porosity are 2 common parameters used by soil engineers to give some indication of structure; however, a comparison of the data given in Table 2 shows that different soils may have the same void ratio but very different pore-size distributions. The pore-size distribution may be as important as the other parameters, or possibly more so, in explaining the mechanistic behavior of soil insofar as it is one means of quantifying soil structure. Further research is needed to correlate parameters that quantify soil structure with other engineering characteristics.

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DISCUSSION

Rodney J. Huang and Arshud Mahmood, University of California, Berkeley

The authors have suggested a soil fabric factor—the ratio of median grain size to void size—as a measure of soil structure. The writers feel that the proposed term implies too wide a connotation, for a meaningful description of fabric must also reflect parameters such as gradations and shapes and arrangements of grains and pores. The ratio d_{50}(grain)/d_{50}(pore), or $\overline{L}/\overline{D}$, could more realistically be called "distribution ratio" (2).

Second, the correlation between the fabric term and the state of soil compaction can be improved when d_{50}(pore)/d_{50}(grain) or $\overline{D}/\overline{L}$ is plotted versus porosity instead of void ratio. The writers have added some data on crushed basalt (23) to the authors' data on loess and Sridharan's data on clays (17). The resulting plot is shown in Figure 8. The numbers of the curves are explained as follows:

No.	Reference	Material
1	17	Grundite
2	17	Kaolinite
3	authors	Loess
4	23	Crushed basalt, fines, minus No. 200 sieve
5	23	Crushed basalt, whole, minus No. 8 sieve

It is tempting to speculate that the slopes and intercepts of various straight-line relations reflect mineral grain properties. The points along each line represent different states of compaction. The authors have identified 4 distinct zones in what is essentially a continuous relation between degree of compaction and particle structure. The writers would like to offer schematics based on the authors' SEM photomicrographs representing those 4 zones (Table 3).

Table 2. Fabric factors of loess and other soils at various void ratios.

Soil	Void Ratio	d_{v50}	d_{s50}	Fabric Factor
Loess (compacted)	1.42	>42	31.5	<0.75
Loess (undisturbed)	0.975	5.8	31.5	5.43
Loess (compacted)	0.975	7.6	31.5	4.15
	0.744	12.7	31.5	2.48
	0.591	3.3	31.5	9.55
	0.427	1.8	31.5	17.5
Kaolinite (sedimented)[a]	1.27	2.0	1.4	0.7
Kaolinite (remolded)[a]	0.85	0.17	1.4	8.3
	0.74	0.12	1.4	11.7
	0.69	0.11	1.4	11.7
	0.59	0.09	1.4	15.6
Boston blue clay (compacted)[a]	0.70	0.19	7.0	3.7
Grundite (compacted illite)[a]	0.57	0.37	1.3	3.5

[a]Data from Sridharan et al. (17).

Figure 8. Medium pore-size to grain-size ratio versus porosity.

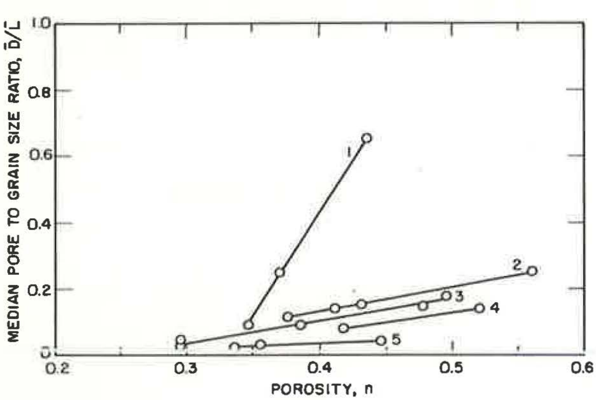
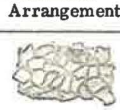
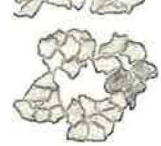


Table 3. Soil structure in relation to compaction effort.

Zone	Structure	Schematic Arrangement	Distribution Ratio	Compaction
A	Altered particle		> 24	Very dense
B	Particulate		24 ~ 6.5	Dense to moderate
C	Composite		65 ~ 1.6	Loose
D	Honeycomb		< 1.6	Very loose

The porosity of a soil can be experimentally related to its strength. One such relationship is given by the exponential equation (22)

$$S = S_o e^{-bn}$$

where

S = strength at porosity n,
S_o = strength at zero porosity,
b = material constant, and
n = porosity.

The logarithmic increase in strength with decreasing porosity is probably a reflection of the exponential variation in the strength of the interparticle forces with changes in the particle spacing. It is suggested that the fabric term introduced by the authors could ultimately be related to the strength of soils by using a relation between porosity and strength. The writers are now attempting such an approach.

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