

Pore Structure of Selected Hawaiian Soils

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Many studies have emphasized that the structure or fabric of deeply weathered tropical soils has important influences on their engineering behavior. This study attempts to characterize the structure of five soils from the island of Oahu, Hawaii, by mercury injection porosimetry. All the soils were derived from basalt, but each had weathered under a different mean annual rainfall. A comparison of air-dried, oven-dried, and freeze-dried samples showed that the method of drying has little effect on the pore size distribution and is interpreted as evidence that the structure of these soils is more stable than that of soils in which the main bonding material is clay. From 89 to 72 percent of the voids in these soils fall within a size range greater than $0.004\text{ }\mu\text{m}$. Although the void ratio variations between these soils do not show any systematic trends, the pore size distributions do. The soils that had developed under wetter climates have higher percentages of pores smaller than $2\text{ }\mu\text{m}$ in diameter and a more uniform pore size distribution. The pore size distributions can be related to the mineral and chemical contents of the soils in that soils weathered in wetter environments are higher in sesquioxide content and lower in kaolinite content.

The engineering behavior of deeply weathered tropical soils in the undisturbed state is largely controlled by their structure, which appears to result from the cementation of the clays by iron oxides (2, 11, 13, 16, 21, 22, 23, 24, 27). For this reason, the Unified and AASHTO classification systems, which are based on engineering index tests using disturbed samples, are inadequate to predict the field performance of these soils (7, 8, 10, 14, 28), and an engineering classification based on parent material and degree of weathering (4, 9, 10, 15) has been recommended.

In an effort to better understand the structure of such soils in relation to their weathering environment, the porosity of five soils, all derived from basalt but weathered under a wide range of mean annual rainfalls, was measured by mercury injection porosimetry tests.

THE SOILS

The soils used in this study were Paaloa, Manana,

Wahiawa, Lahaina, and Molokai soils from Oahu, Hawaii. All were derived from the Koolau basalt series on the leeward side of the Koolau mountain range. Since this basalt series is uniform chemically and petrologically (26) it may be assumed that all of the soils were derived from essentially the same parent rock. These rocks are described as Pliocene olivine basalt flows, which dip from the crest of the mountain range at angles of 3 to 10 deg. The basalt has a high permeability, resulting from interstitial spaces in the clinkers, shrinkage cracks, and gas vesicles (18, 19).

The soils are classified as Oxisols and Ultisols. All have a seasonal high water table deeper than 150 cm and bedrock at depths greater than 150 cm. A complete morphologic description and other physical and chemical data are given by Foote and others (7).

The sample locations are along a 5-km traverse on the divide between Kipapa Stream and Panakauki Gulch about 5.5 km northwest of Pearl City. The elevations of the sample sites range from about 165 to 365 m. Since the rainfall is orographic, there is a mean annual precipitation of 58 to 216 cm/year. The slopes on which the soils formed range from 2 to 7 percent. The pedologic classification and environmental factors are given below.

Soil Series	Pedologic Classification	Mean Annual Rainfall (cm/year)	Slope (%)
Molokai	Typic torrox	58	2
Lahaina	Typic torrox	71	2
Wahiawa	Tropeptic eutrustox	127	2
Manana	Orthoxic tropohumult	158	7
Paaloa	Himoxic tropohumult	216	7

Samples were collected from the B horizon of each soil series at depths of 25 to 135 cm in thin-walled Shelby tubes 7.62 cm in diameter and about 25 cm long. Three borings were made at each location and samples taken from various depths. The range of sampling depths for each series is shown in Table 1. The engineering index properties of these soils are also listed in Table 1 although they do not correlate with the porosimetry data.

METHOD

The use of mercury injection porosimetry to characterize the pore size distribution of soils in order to relate the soil structure to its engineering properties was introduced by Diamond (6). Since then several related studies on compacted soils (1, 3, 17) have been conducted. The technique is based on the Washburn (25) equation

$$P = (-2T \cos \theta)/r \quad (1)$$

where P is the pressure, T is the surface tension, θ is the angle of contact, and r is the pore radius. The soil samples were dried and placed in the sample cell of the porosimeter, and the sample space was then evacuated with a vacuum pump so that air would not block the flow of mercury into the pores of the sample. After evacuation of the pressure chamber, mercury was allowed into it to immerse the soil sample. Since the volume of the chamber is known and the volume of mercury that flows into it can be measured, the total volume of the sample can be calculated. Then, as pressure is applied, the mercury penetrates the sample. Both the volume of mercury penetrating the soil and the pressure required to cause this penetration are measured, and these data are used in equation 1 to compute the pore radius that is being penetrated at a given pressure. These results are then plotted to give the pore size distribution curve.

The instrument used in this study has a pressure range of 0.035 to 3500 kg/cm². With it, if the surface tension of mercury is taken as 47.4 mN/m and a contact angle of 140 deg is used, it is possible to measure pore radii between 105.4 and 0.00210 μm . This porosimeter also has the capability to empty the pores by reducing the pressure to produce a vacuum at the end of the penetration phase. This allows measurement of the pore size distribution on the extrusion cycle and, from those data, a characterization of the irregularity of the pores.

OBSERVATIONS

The influence of drying methods was evaluated for all of the soils by taking three portions of soil from the same boring and depth, and air-drying one, oven-drying the second at 100°C, and freeze-drying the third. Figure 1 shows that there is little or no difference in the pore size distribution curves for samples of the same soil dried by the different techniques. The same behavior is true of all five soil series and contrary to the results of Ahmed and others (1). This observation supports the conclusions of other studies on tropical soils that the clays are cemented together by iron oxides. If the clays themselves were the main source of bonding in these soils, significant volume changes would result from air- and oven-drying as compared with freeze-drying.

Pore size distribution determinations were made for 6 to 10 samples from various depths and borings of each series. Figure 2 shows the range of pore size distribution curves for 9 samples of the Paaloa soil series, which is typical for all of the series. The variation in pore size characteristics within a soil series is fairly small.

On the other hand, when the pore size characteristics of the various series are compared, there is a wide range in the curves as shown in Figure 3. From these curves, each of which is representative of a soil series, it is possible to generate a set of parameters to characterize the pore structure of each series.

Some similarities in the curves are observed. For example, the Molokai, Lahaina, and Wahiawa series all show a distinct bimodal distribution, one in the 10 to

20- μm size range and the other in the 0.01 to 0.1- μm range. The other two soils show only the smaller size range. These quantitative data support earlier qualitative studies made with a scanning electron microscope (23).

The extrusion curves were plotted to describe the pore diameter versus volume relation as the mercury was removed from the soil. In all soils there is a considerable hysteresis loop that indicates the necking down of the pores. A typical curve having a hysteresis loop is shown in Figure 4. The volume of mercury that is retained in the sample at the end of the evacuation is a measure of the nonuniformity of the pore size distribution. The percentage of the total amount of mercury injected into the samples that was retained in the soil varied from 36 to 55 percent. The values for each series are shown in Table 2. Table 2 also shows the following other pore size characterization parameters: the median (50 percent) and small mode pore diameters, the uniformity coefficient, the percentage of pores smaller than 2 μm , and the void ratios computed both from mercury injection data and from measurements of the bulk geometry of the Shelby tube samples and the dry weight of the samples. The uniformity coefficient is defined, by analogy with the uniformity coefficient calculated from particle size distribution curves, as the ratio of the minimum pore diameters corresponding to 60 and 10 percent of the total pore volume penetrable by mercury respectively.

Comparison of the void ratios calculated from the mercury injection data with those calculated from the bulk density measurements shows that not all of the voids were intruded by the mercury. That is, there is a considerable volume of pores having diameters smaller than 0.004 μm . The portion of pore volume not intruded by mercury, expressed as a percentage of the total volume as measured by bulk density, is about 11 percent for the Molokai soil and ranges from about 21 to 28 percent for the other four. From these data the pore size parameters can be computed on the basis of the total pore volume rather than on the basis of the pore volume intruded by the mercury; but, although there are small changes in the values of the parameters such as the percentage of pores smaller than 2 μm and median pore diameter, the trends, which are observed as the five soil series are compared, do not change. For convenience, all of the pore size parameters reported here are based on the volume of pores intruded by mercury.

RELATIONSHIP OF PORE SIZE TO WEATHERING AND MINERALOGY

The soils are listed in Table 2 in order of increasing mean annual precipitation. Although there is no apparent relation between the void ratio and the amount of rainfall, there are trends between other pore size parameters and rainfall. This emphasizes the usefulness of information related to pore size as opposed to information based on total pore volume only. Data both on the percentage of mercury retained at the end of the withdrawal cycle and on the uniformity coefficient show that the soils that have developed under wetter climates have a more uniform distribution of pore sizes than those developed under drier climates. The small pore mode diameters range from 0.014 to 0.031 μm , and the wetter soils have larger mode pore sizes. There is no clear trend for the median diameter or for the total pore volume. The percentage of pores smaller than 2 μm increases systematically from soils developed under drier climates to those developed in wetter areas. The mineral and other chemical constituent contents of the soils (based on B horizon data of the Soil Conservation Service) are shown below.

Table 1. Engineering index properties.

Soil Series	Gradation			Liquid Limit	Plasticity Index	Specific Gravity	Range of Sample Depths (cm)
	Sand (%)	Silt (%)	Clay (%)				
Molokai	28.7	51.1	20.3	45.5	6.8	2.946	43 to 135
Lahaina	31.0	38.8	30.3	49.1	10.6	2.937	48 to 122
Wahiawa	10.7	45.6	43.8	51.3	15.3	2.989	34 to 104
Manana	69.3	16.7	14.0	67.1	16.7	2.991	25 to 124
Paaloa	27.8	39.3	33.0	57.1	17.8	3.098	38 to 135

Note: 1 cm = 0.4 in.

Table 2. Pore size parameters.

Soil Series	Void Ratio by Mercury Injection	Void Ratio by Bulk Measurement	Median Pore Diameter (μm)	Small Pore Mode Diameter (μm)	Uniformity Coefficient ($\times 10^{-1}$)	Mercury Retained (%)	Pores $\leq 2 \mu\text{m}$ (%)
Molokai	0.960	1.085	0.037	0.015	4.3	55.2	61.5
Lahaina	0.919	1.276	0.019	0.014	8.4	47.6	70.5
Wahiawa	0.723	1.011	0.017	0.015	8.9	50.0	79.0
Manana	0.978	1.237	0.023	0.022	28.1	36.1	84.0
Paaloa	1.029	1.321	0.038	0.031	30.7	40.4	85.0

Note: $1 \mu\text{m} = 4 \times 10^{-5}$ in.

Figure 1. Effect of drying method on cumulative pore size distribution.

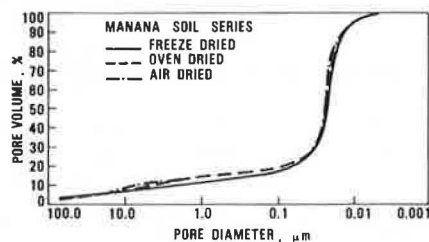


Figure 2. Example of variation of pore size distribution within Paaloa soil series.

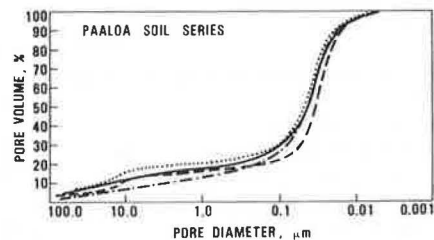


Figure 3. Cumulative pore size distribution curves for five soil series.

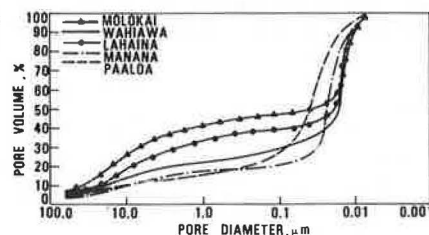
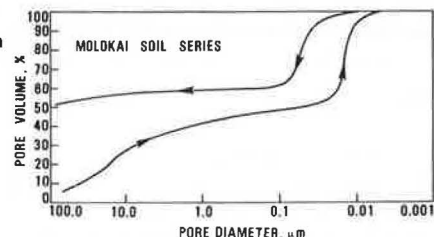


Figure 4. Typical pore size distribution curve including hysteresis loop.



Soil Series	Kaolinite	Gibbsite	Iron Oxide	Kaolinite
				Gibbsite + Iron Oxide
Molokai	53	0	12.1	4.38
Lahaina	52	2	16.0	2.89
Wahiawa	53	6	13.6	2.70
Manana	30	11	20.9	0.94
Paaloa	12	34	25.8	0.20

The kaolinite content decreases with increasing rainfall (5, 12, 20), and the gibbsite and total iron oxide contents both increase with increasing rainfall. The systematic trend is indicated by the variation of the kaolinite to gibbsite plus iron oxide ratios with rainfall. From these trends it appears that both the aluminum and iron oxides may be involved in the cementation of the clays. According to the weathering model of Alexander and Cady (2), as the kaolinite is weathered to gibbsite there may be more cementation, which would result in a higher percentage of smaller pores and a more uniform size range of those pores.

SUMMARY AND CONCLUSIONS

Tests on five basalt-derived soils from Oahu showed that mercury injection porosimetry can be used to char-

acterize the pore size distribution of these deeply weathered tropical soils. The method of drying the soil has little effect on the pore size distribution. This is interpreted as evidence that the structure of these soils is more stable than that of soils in which the main bonding material is clay. From 89 to 72 percent of the voids are within the size range greater than $0.004 \mu\text{m}$. Although the void ratio of the soils does not show any systematic trends in relation to the mean annual rainfall, the soils that developed under wetter climates have higher percentages of smaller pores and pores of a more uniform size distribution. These data can also be related to the mineral contents of the soils in that the soils that had weathered in wetter environments are higher in sesquioxide content and lower in kaolinite content.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support for this work by a grant from the Army Research Office and the additional support of the Engineering Research Institute at Iowa State University. They also thank Oran Bailey, U.S. Department of Agriculture, who helped select the sampling sites and provided pedogenic and chemical data on the soils studied.

REFERENCES

1. S. Ahmed, C. W. Lovell, Jr., and S. Diamond. Pore Sizes and Strength of Compacted Clay. *Journal of the Geotechnical Engineering Division, Proc., ASCE*, Vol. 100, 1974, pp. 407-425.
2. L. T. Alexander and J. G. Cady. Genesis and Hardening of Laterite in Soils. U.S. Department of Agriculture Technical Bulletin 1282, 1962.
3. W. W. Badger and R. A. Lohnes. Pore Structure of Friable Loess. HRB, Highway Research Record 429, 1973, pp. 14-23.
4. H. S. Bhatia. Discussion of Engineering Characteristics of Laterites. *Proc., Specialty Session of Engineering Properties of Lateritic Soils, 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City, Vol. 2, 1970*, pp. 75-80.
5. L. A. Dean. Differential Thermal Analysis of Hawaiian Soils. *Soil Science*, Vol. 63, 1947, pp. 95-105.
6. S. Diamond. Pore Size Distribution in Clays. *Clays and Clay Minerals*, Vol. 18, 1970, pp. 7-23.
7. D. E. Foote, E. L. Hill, S. Nakamura, and F. Stevens. Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii. Soil Conservation Service, U.S. Department of Agriculture, and Agricultural Experiment Station, Univ. of Hawaii, 1972.
8. B. Fruhauf. A Study of Lateritic Soils. *Proc., HRB*, Vol. 26, 1946, pp. 579-589.
9. M. D. Gidigas. The Importance of Soil Genesis in the Engineering Classification of Ghana Soils. *Engineering Geology*, Vol. 5, 1971, pp. 117-161.
10. A. L. Little. The Engineering Classification of Residual Tropical Soils. *Proc., Specialty Session on Engineering Properties of Lateritic Soils, 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City, Vol. 1, 1969*, pp. 1-10.
11. R. A. Lohnes, R. O. Fish, and T. Demirel. Geotechnical Properties of Selected Puerto Rican Soils in Relation to Climate and Parent Rock. *Geological Society of America*, Vol. 82, 1971, pp. 2617-2624.
12. R. A. Lohnes and R. L. Handy. Shear Strength of Some Hawaiian Latosols. 6th Annual Symposium on Engineering Geology and Soil Engineering, Boise, Idaho, 1968.
13. R. A. Lohnes and T. Demirel. Strength and Structure of Laterites and Lateritic Soils. *Engineering Geology*, Vol. 7, 1973, pp. 13-33.
14. Z. C. Moh and F. M. Mazhar. Effects of Method of Preparation on Index Properties of Lateritic Soils. *Proc., Specialty Session on Engineering Properties of Lateritic Soils, 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City, Vol. 1, 1969*, pp. 23-36.
15. D. G. Moye. Engineering Geology for the Snowy Mountains Scheme. *Civil Engineering Transactions, Institution of Engineers, Australia*, Vol. 27, 1955.
16. S. Sivarajasingham, L. T. Alexander, C. G. Cady, and M. G. Cline. Laterite. In *Advances in Agronomy*, Academic Press, New York, Vol. 14, 1962, pp. 1-60.
17. A. M. Sridharan, A. G. Altschaeffl, and S. Diamond. Pore Size Distribution Studies. *Journal of the Soil Mechanics and Foundations Division, Proc., ASCE*, Vol. 97, No. SM5, 1971, pp. 771-787.
18. H. T. Stearns. *Geology of the State of Hawaii*. Pacific Books, Palo Alto, Calif., 1966.
19. H. T. Stearns and K. N. Vaksvid. *Geology and Ground-Water Resources of the Island of Oahu*, Hawaii. Hawaii Division of Hydrography Bulletin, No. 1, 1935.
20. T. Tanada. *Hawaiian Soil Colloids*. Agricultural Experiment Station, Univ. of Hawaii, Rept., 1942-1944, pp. 56-57.
21. K. Terzaghi. Design and Performance of Sasumua Dam. *Proc., Institute of Civil Engineers*, Vol. 9, 1958, pp. 369-395.
22. F. C. Townsend, P. G. Manke, and J. V. Parcher. Effects of Remolding on the Properties of the Lateritic Soil. HRB, Highway Research Record 284, 1969, pp. 76-84.
23. G. Y. Tsuji, R. T. Watanabe, and W. S. Sakai. Influence of Soil Microstructure on Water Characteristics of Selected Hawaiian Soils. *Proc., Soil Science Society of America*, Vol. 39, 1975, pp. 28-33.
24. K. B. Wallace. Structural Behaviour of Residual Soils of the Continually Wet Highlands of Papua New Guinea. *Geotechnique*, No. 2, 1973, pp. 203-218.
25. E. W. Washburn. Note on a Method of Determining the Distribution of Pore Sizes in a Porous Material. *Proc., National Academy of Sciences*, Vol. 7, 1921, pp. 115-116.
26. C. J. Wentworth and H. Winchell. Koolau Basalt Series, Oahu, Hawaii. *Bulletin of the Geological Society of America*, Vol. 58, 1947, pp. 46-78.
27. H. F. Winterkorn and E. C. Chandrashekharan. Laterite Soils and Their Stabilization. HRB, Bulletin 44, 1951, pp. 10-29.
28. F. L. D. Wooltorton. *The Scientific Basis of Road Design*. Edward Arnold Publishers, London, 1954.