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"Soil Porosity"

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SOIL POROSITY 1/

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Soil porosity is a vital aspect of the study of soil physics. It has a marked influence on most soil physical properties and processes. Large pores are critically important for transmission of air and water, and the smaller ones are those where the interactions at the molecular level take place and are critically important in terms of the forces holding domains and aggregates of primary particles together (Greenland, 1977). Between these size limits are the pores which hold water against gravity and release it to plants. Greenland (1977) suggested another group of pores which rarely loose water in the field but are important as a reservoir of nutrient ions and in providing a medium for action of interparticle forces.

Damage to soil structure is often in the form of a decrease of total pore space and/or a change in pore-size distribution with a decrease in the proportion of pore space in transmission and storage pores.

In this brief presentation I shall discuss several aspects of soil porosity, mainly in terms of describing the physical constitution of the soil material as expressed by the spatial arrangement of the soil particles and associated voids. Discussion will include: soil porosity, aeration porosity, aeration capacity, pore-size distribution, classification of pores, textural and structural porosity, and structural porosity index.

Soil Porosity. Soil porosity is the volume fraction of ~~pore~~ space not occupied by soil particles in a bulk volume of soil. Soil porosity generally lies in the range 0.3-0.6. Coarse-textured soils tend to be less porous than fine-textured soils, though the mean size of individual pores is greater in coarse-textured soils. The total porosity reveals no information about the pore-size distribution.

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Soil porosity can be calculated from knowledge of bulk and particle densities:

$$E = (1 - \rho_b/\rho_p) \qquad [1]$$

where ρ_b and ρ_p are bulk and particle densities, respectively. If a soil had bulk and particle densities of 1.3 and 2.6 Mg/m^3, respectively, then its porosity would be 0.5.

Aeration Porosity. Aeration porosity, air porosity, and air-filled porosity are all terms used for the proportion of the bulk soil volume that is filled with air at any given time or under a given condition such as a specified soil water content or soil water matric potential. Aeration porosity equals soil porosity minus volumetric water content. If a soil had a porosity of 0.50 and a volumetric water content of 0.30, then the aeration porosity would be 0.20.

As water content varies widely in a wetting and drying cycle, so does aeration porosity. That is indicated by the arrows of Fig. 1. An increase in air or water is associated with a decrease in the other. In swelling soils, bulk density is not constant with change in water content as illustrated in Figs. 2 and 3. As a swelling soil is wetted, total porosity increases and pore-size distribution changes.

Soils that have low aeration porosities extending into the plant growth range of soil water are likely to experience limited aeration. Greeland (1979) suggested that at least 10 percent of the soil volume needs to consist of pores in the range 0.5 to 50 μm as it is these pores which store the water used by the plant. There should also be at least 10 percent of the pore volume contained in pores greater than 50 μm to allow water to drain freely through the soil. Typical relationships between aeration porosity and matric potential are shown for fine (clay) and coarse (sand) textured soils in Fig. 4. At matric potential of -20 J/kg, aeration porosities are 0.10 and 0.35 for clay and sand, respectively, thus

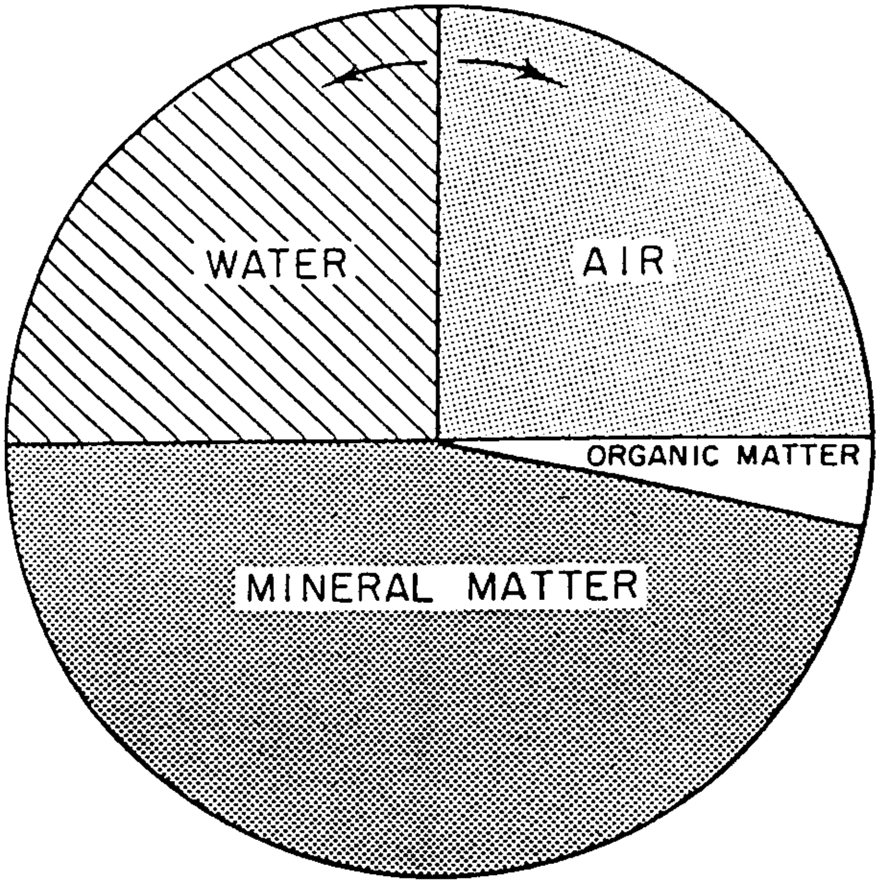

Fig. 1. Schematic composition of a medium-textured soil at a water content considered favorable for plant growth.

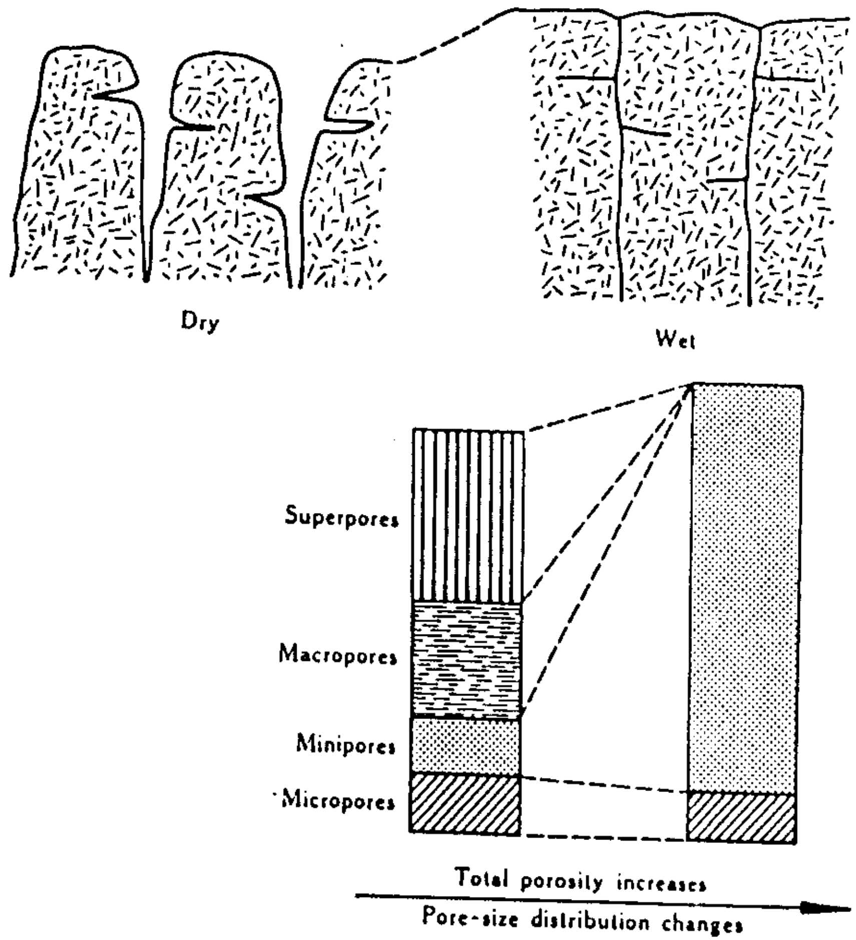

Fig. 2. Porosity changes in swelling soils (McIntyre, 1974).

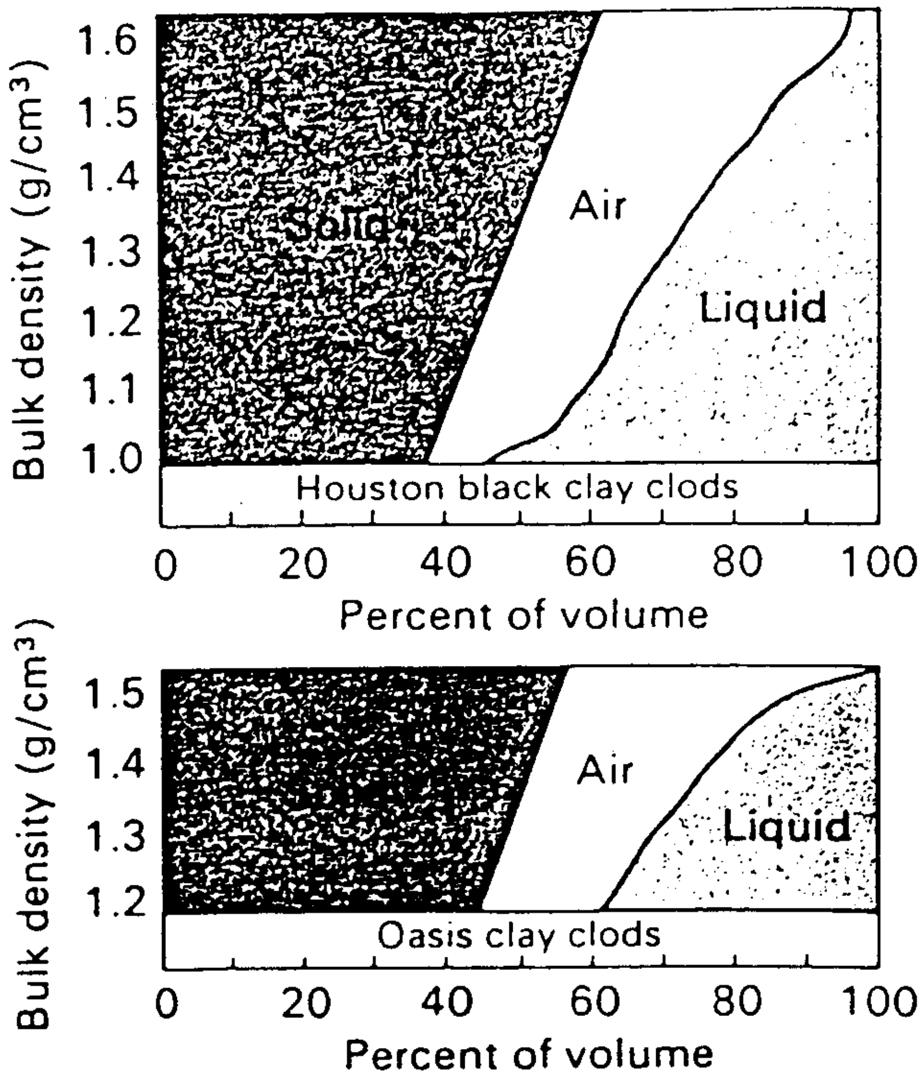

Fig. 3. Relation between the volume percentages of solid, air, and liquid in a soil sample as a function of bulk density. As the soil dries out, it shrinks, the bulk density increases, and the percentage of the volume occupied by solid increases. Thus, the increase in the amount of air is not directly proportional to the volume of water removed. The effect is more marked in the Houston black clay clods than in the Oasis clay clods (Taylor and Ashcroft, 1972).

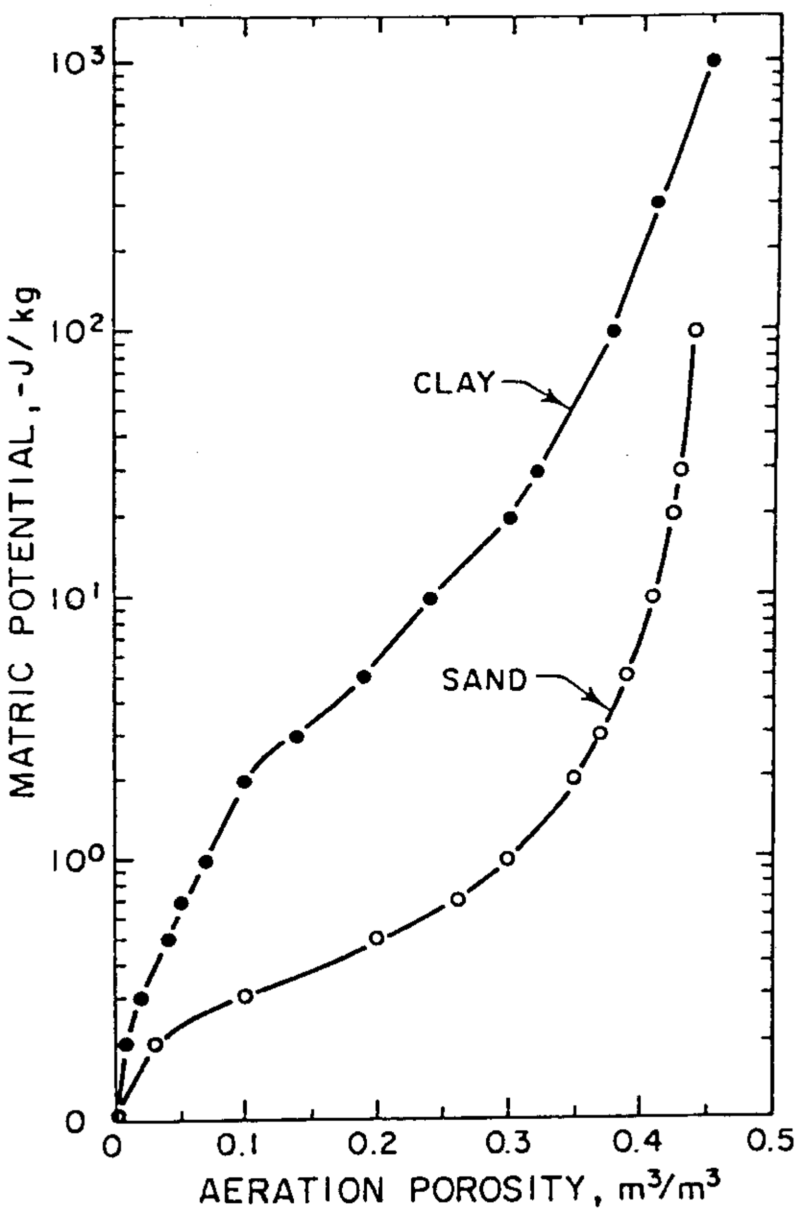

Fig. 4. Relation between aeration porosity and water matric potential for typical clay and sand soils (adapted from Hillel, 1977).

indicating much slower water infiltration and transmission in the clay soil than in the sand. Under wet conditions, plants growing in the clay soil may not have sufficient oxygen. On the other hand the changes in aeration porosity between a matric potential of -20 J/kg and -1500 J/kg for the clay and sand are 0.29 and 0.09, respectively. Approximately three times as much water can be stored in the "plant-available range" in the clay soil as in the sand.

Aeration Capacity. Aeration capacity is the aeration porosity of soil when its water content is at field capacity. Baver (1956) found that an air capacity of at least 0.08 to 0.10 was necessary for good growth of sugar beets on clay soils. Because field capacity is not a precise value, the term aeration capacity is also not precise.

Pore-size Distribution. Pore-size distribution represents the volume of the various sizes of pores in a soil. It is expressed as a percentage or fraction of the bulk volume and can be visualized from water-release characteristic curves. An equivalent pore diameter, EPD, can be calculated from the Kelvin equation

$$EPD = 4\gamma \cos \theta/\psi_m \qquad [2]$$

where γ is surface tension of water, θ is contact angle, and ψ_m is matric water potential. Although the equation is considered valid only at relatively high water potentials (wet soil), we have used it to illustrate relative pore-size distribution at various water potentials (Table 1, Fig. 5).

Matric potential of soil water at field capacity ranges between -10 and -30 J/kg for most soils. That corresponds to an equivalent pore diameter of largest water filled pores of 10 to 30 μm (Fig. 5). Pores that are empty of water at field capacity are usually referred to as macro or transmission pores (Table 2). Equivalent pore diameter of largest water filled pores at "permanent wilting point" (-1500 J/kg matric potential) is 0.2 μm. At that water potential the soil water is more adsorbed than absorbed and closely associated with the surface area of the soil particles.

Table 1. Pore-size distribution of representative clay and sand. Adapted from water characteristic curves of Hillel (1977, p. 81).

Matric potential		EPD†	Volumetric water content‡		Air-filled porosity§	
m (H_2O)	J/kg	μm	Sand	Clay	Sand	Clay
			m³/m³			
0.1	1.0	288.	0.45	0.52	0	0
0.2	1.97	146.	0.42	0.51	0.03	0.01
0.3	2.95	97.8	0.35	0.50	0.10	0.02
0.5	4.92	58.6	0.25	0.48	0.20	0.04
0.7	6.88	41.9	0.19	0.47	0.26	0.05
1.0	9.83	29.3	0.15	0.45	0.30	0.07
2.0	19.7	14.6	0.10	0.42	0.35	0.10
3.0	29.5	9.8	0.08	0.38	0.37	0.14
5.0	49.2	5.86	0.06	0.33	0.39	0.19
10.0	98.3	2.93	0.04	0.28	0.41	0.24
20.0	196.7	1.47	0.025	0.225	0.43	0.30
30.0	295.0	.98	0.02	0.200	0.43	0.32
50.0	491.6	.58				
100.	983.3	.293	0.01	0.140	0.44	0.38
300.	2,950.	.098		0.11		0.41
1,000.	9,833.	.029		0.075		0.45
15,000.	14,749.	.020		0.035		0.49

† Equivalent pore diameter.

‡ The values for volumetric water content also represent the fractional soil volume consisting of pores ≤ equivalent pore diameter.

§ Air-filled porosity equals total porosity minus volumetric water content.

Table 2. Classification of soil pores.

EPD+ (μm)	Exp_{10}	Water potential (J/kg)	Exp_{10}	IUPAC (1972)	McIntyre (1974)	Smart (1975)	Greenland (1977)
5.0	3	-5.76	-2		Super pores		
2.0	3	-1.44	-1			Mini pores	Fissures
5.0	2	-5.76	-1				
2.0	2	-1.44	0		Macro pores		Transmission pores
5.0	1	-5.76	0	Macro pores		Macro pores	
2.0	1	-1.44	1				
5.0	0	-5.76	1				Storage pores
2.0	0	-1.44	2		Mini pores	Micro pores	
5.0	-1	-5.76	2				
2.0	-1	-1.44	3				
5.0	-2	-5.76	3				Residual pores
2.0	-2	-1.44	4	Meso pores	Micro pores	Ultra micro pores	
5.0	-3	-5.76	4				
2.0	-3	-1.44	5	Micro pores			Bonding pores

+ EPD = equivalent pore diameter of largest water filled pores calculated from $\psi_m = 4\gamma \cos\theta/d$ for $\gamma = 71.97$ dynes/cm at 25°C and $\cos\theta = 1$ where d is EPD.

Based on the relationship of Fig. 5 and a water release characteristic curve for a typical clay and sand soil (Hillel, 1977), we calculated the fractional soil volume consisting of pores less than a certain size (Fig. 6). The volumes of pores in Greenland's (Table 2) transmission range (50-500 μm) are 0.04 and 0.24 m^3/m^3 for clay and sand, respectively. The volumes of pores in the storage range (0.5-50 μm) are 0.32 and 0.20 for clay and sand, respectively. That illustrates, as did Fig. 4, slow transmission and possible aeration problems in the clay and rapid transmission and low water storage of the sand.

In general, the greater the clay content, the greater the water retention at any particular water potential and the more gradual the slope of the soil-water characteristic curve. In a sandy soil, most of the pores are relatively large, and once these large pores are emptied at a given water potential, only a small amount of water remains. In a clayey soil, the pore-size distribution is more uniform and more of the water is adsorbed so that increasing the matric suction causes a gradual decrease in water content.

Textural and Structural Porosity. Another classification of pores is textural and structural porosity. Fies (Avignon, France - Steve Rawlins trip report) refers to structural porosity as the porosity between aggregates and textured porosity as the porosity within aggregates. Hillel (1980) suggested that the amount of water retained between 0 and -100 J/kg depends primarily upon the pore-size distribution and hence is strongly affected by soil structure. On the other hand, water retention in the higher suction range is due increasingly to adsorption and is thus influenced less by the structure and more by texture. However, it should be noted that many sandy soils are structureless and that the water retained in them at low suction depends primarily upon pore-size distribution between individual particles rather than between aggregates.

Structural Porosity Index. The change in structural porosity caused by various treatments indicates relative stability of soil structure and/or severity

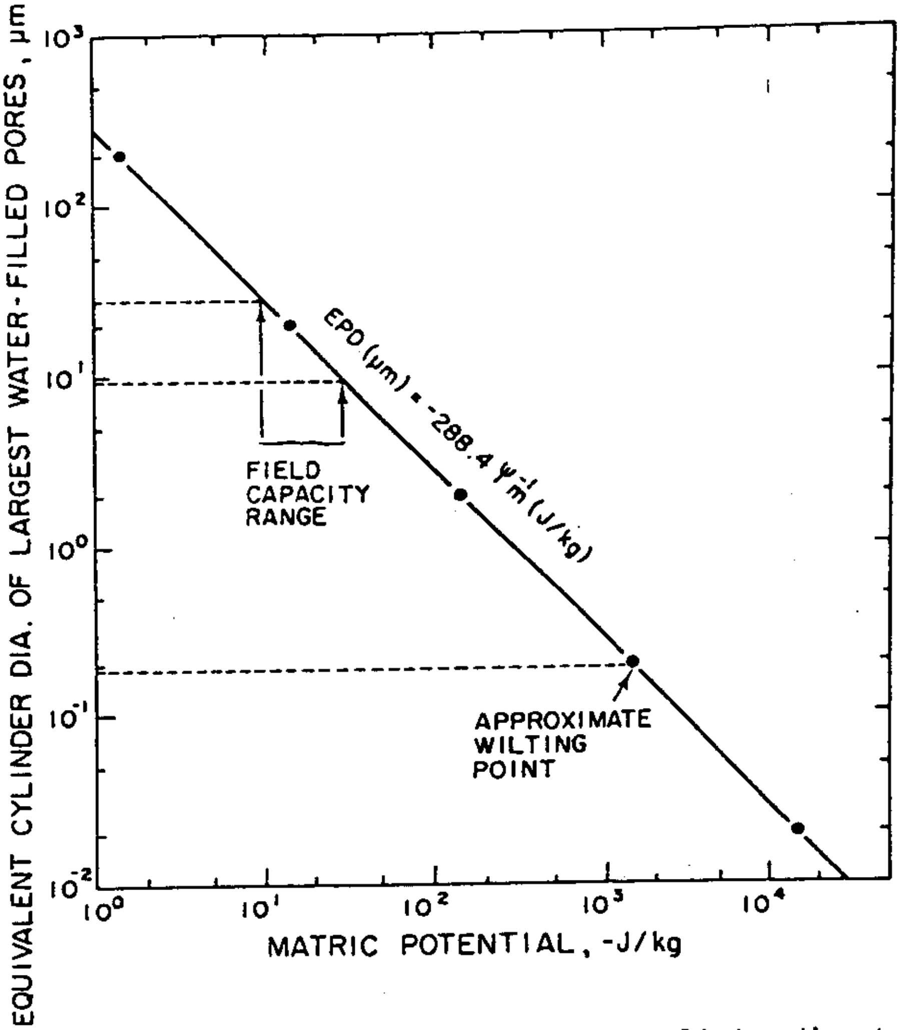

Fig. 5. Relation between equivalent cylinder diameter of largest water-filled pores and matric potential.

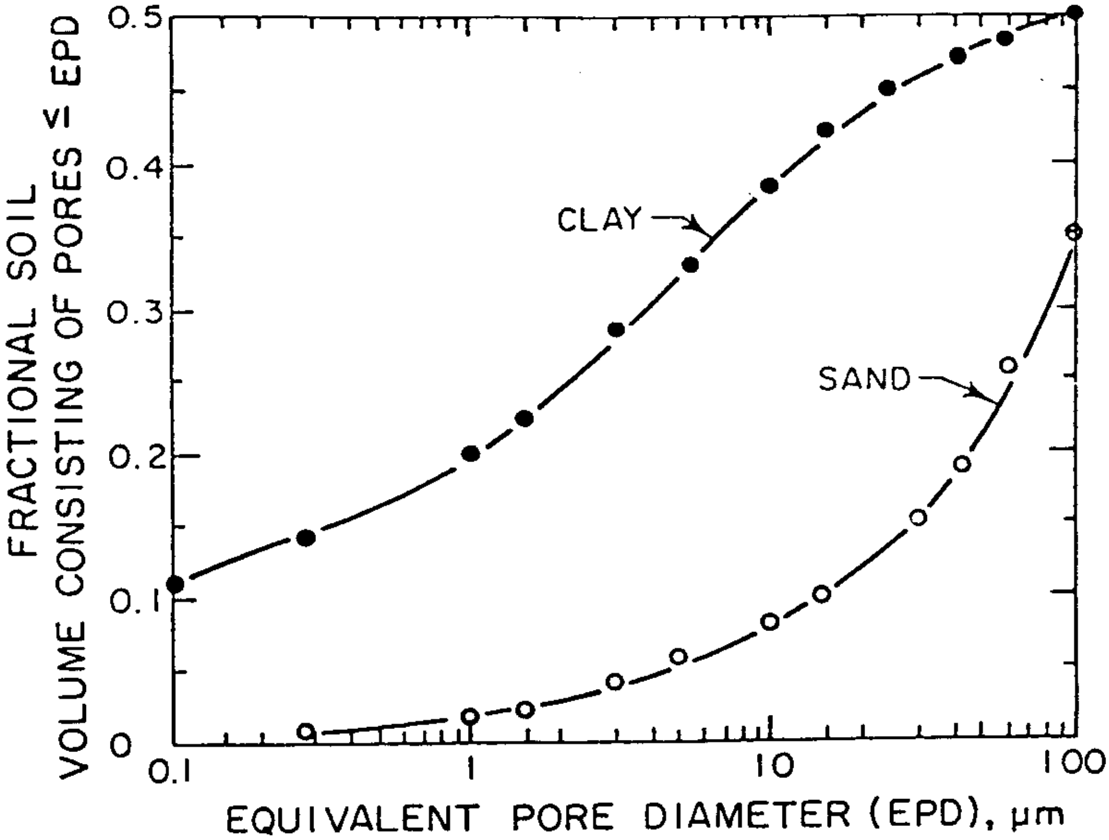

Fig. 6. Pore-size distribution of a clay and a sand soil.

of treatment. Childs (1940) cited by Taylor and Ashcraft (1972) determined the stability of a Gault clay by comparing slope of water characteristic curves of subsequent wetting and drying cycles.

Marked change of soil-water characteristic curve caused by soil manipulation is shown in Fig. 7. The structure was completely destroyed for the sonicated treatment whereas for the crush/sieve treatment the aggregates were crushed so as to pass through a 1.0 mm sieve before determining water-release characteristics. Since the soils are all the same texture, it is expected that the curves will coincide as the water retained is influenced more by particle surface area and less by pore-size distribution.

Data of Fig. 7 may be analyzed to yield a structural porosity index by comparing the air-filled porosity of a structure destroyed soil to the air-filled porosity of a structured soil over a specified portion of the low suction range of the water-release characteristic curve. Data of Fig 7 were used to construct the curves of Fig. 8 in the -1 to -10 kPa soil-water pressure range. The comparison can be made by

$$SPI = \int_0^1 [s(x) - t(x)]dx \qquad [3]$$

where SPI is structural porosity index, m^3/m^3; s(x) is air-filled porosity as a function of $\log_{10}$ (soil-water suction, kPa) defined between 0 and 1.0 for the soil in question; t(x) is air-filled porosity as a function of $\log_{10}$ (soil-water suction, kPa) defined between 0 and 1.0 for a soil whose aggregation has been destroyed.

Then from the equations given in Fig. 8, structured porosity index for the nondisturbed soil is

$$SPI_1 = \int_0^1 [0.18 + 0.04\ x) - (0.04 + 0.03\ x)]dx = 0.145\ m^3/m^3 \qquad [4]$$

and for the crush/sieve soil

$$SPI_2 = \int_0^1 [(0.10 + 0.13\ x) - (0.04 + 0.03\ x)]dx = 0.11\ m^3/m^3. \qquad [5]$$

The noncultivated Reading silt loam soil used in this example was well structured, with an abundance of transmission-size pores. Even the crush/sieve

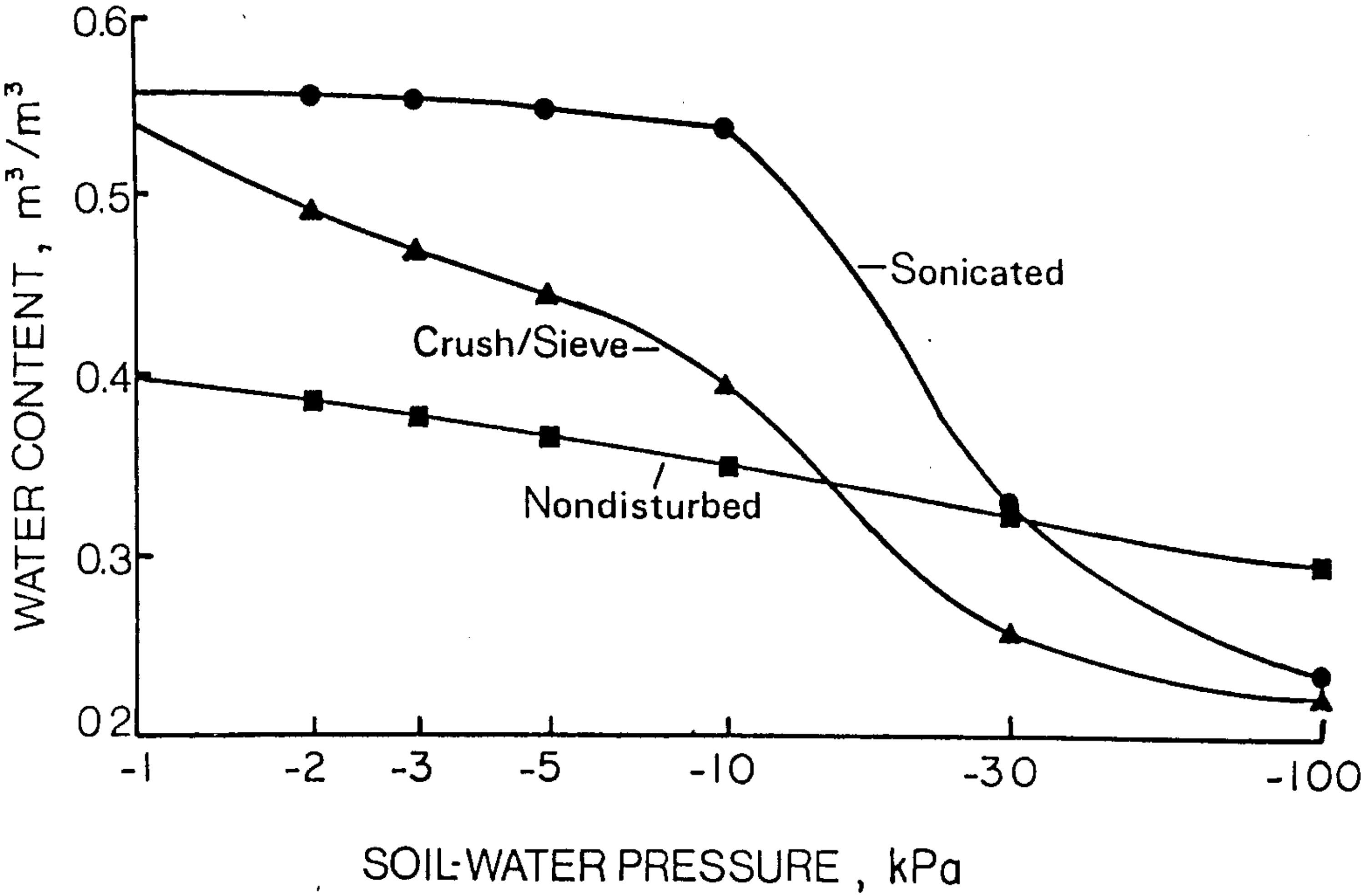

Fig. 7. Soil-water characteristics of noncultivated Reading silt loam for indicated treatments.

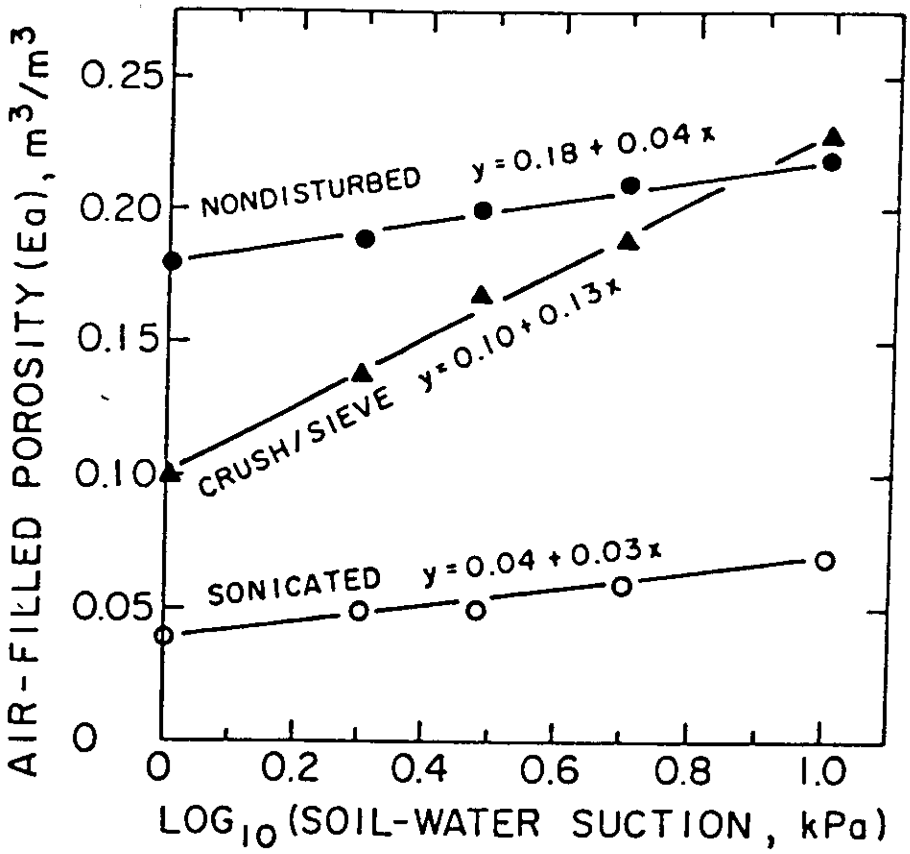

Fig. 8. Air-filled porosity as influenced by indicated treatments of Reading silt loam at low soil-water suctions.

treatment had 11 percent by volume of air-filled pore space in the soil moisture range between 1 and 10 kPa pressure.

The structural porosity index as just illustrated shows promise for evaluating structural degradation of soils and the influence of various conservation tillage practices on soil structure.

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