Porosity and Pore-Size Distribution of Soil Aggregates

by

Shen-maw Lin

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FOREWORD

This Bulletin is published in furtherance of the purposes of the Water Resources Research Act of 1964. The purpose of the Act is to stimulate, sponsor, provide for, and supplement present programs for the conduct of research, investigations, experiments, and the training of scientists in the field of water and resources which affect water. The Act is promoting a more adequate national program of water resources research by furnishing financial assistance to non-federal research.

The Act provides for establishment of Water Resources Research Institutes or Centers at Universities throughout the Nation. On September 1, 1964, a Water Resources Research Center was established in the Graduate School as an interdisciplinary component of the University of Minnesota. The Center has the responsibility for unifying and stimulating University water resources research through the administration of funds covered in the Act and made available by other sources; coordinating University research with water resources programs of local, State and Federal agencies and private organizations throughout the State; and assisting in training additional scientists for work in the field of water resources through research.

This report is the twenty-ninth in a series of publications designed to present information bearing on water resources research in Minnesota and the results of some of the research sponsored by the Center. In this investigation the research was directed towards providing a better understanding of aggregate porosity due to soil type, aggregate size and cultivation condition. Experiments were designed to measure aggregate porosity under two methods: glassbead displacement and thin sectioning. The results of the research shed light on soil phenomena such as aeration, storage and movement of water which are frequently determined by the characteristics of the soil pore system.

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INTRODUCTION

The total amount, size distribution, and configuration of air voids in soils are thought to be important indices in evaluating soil structure. Many soil phenomena such as aeration, storage and movement of water are frequently determined by the characteristics of the pore system. Air voids are also important in investigations of the development of plant roots, of heat flow and of soil strength.

The porosity and pore-size distribution are largely determined by the size, shape and arrangement of soil aggregates. Any change in soil structure can result from changes in the volume of aggregates and air voids and a change of pore sizes.

Porosity and pore-size distribution are strongly affected by cultivation. Traffic by farm machinery often causes a high degree of soil compaction and lowers the total porosity. Implements such as planters and harvesters contribute to decreasing porosity and deforming soil aggregates. Porosity and pore-size distribution are also affected by texture. Fine-textured soils tend to have higher porosity than coarse soils and a clay soil which contains many fine particles tends to have a relatively high amount of small pores. Organic matter also plays an active part in developing the pore system since it is an important factor in aggregate stabilization. In addition, porosity and pore volume of the large pores also depend on aggregate size.

A distinction is made between intraaggregate and interaggregate porosities in structured soil. Intraaggregate porosity is that existing within the aggregates while interaggregate porosity is that existing between aggregates. Both large pores and small pores are co-existant in the interaggregate and intraaggregate pore spaces. Large pores are relatively abundant between aggregates, whereas small pores are mostly found within aggregates.

Various measurements of porosity and pore-size distribution have been developed. Methods employing mercury intrusion and non-polar liquid displacement have been known for a long time. Two other methods were developed more recently. They are glassbead displacement and thin sectioning.

The author was interested in studying the characteristics of pores within aggregates and some of the factors that influence them. Aggregate porosity as a function of soil type and of aggregate size were of primary concern. Differences in aggregate porosity due to cropping and remolding in the laboratory were also of interest. In addition, information of pore-size distribution was also sought.

Experiments were designed to measure aggregate porosity under two methods: glassbead displacement and thin sectioning. Four size fractions of aggregates were prepared from 0.5-1, 1-3, 3-5 and 5-8 mm in diameter. Measurements were made on six soil types. A virgin and a cultivated sample were collected for each soil type. Effect of remolding of aggregates on pore characteristics was measured. Pore-size distribution was determined by Hg-porosimetry.

REVIEW OF LITERATURE

Importance of Pore Volume to Plant Growth

Though this thesis does not deal specifically with relationships between pore characteristics and plant growth, the ultimate objective of the research is to better understand the environment in which plant roots live. Inferences of the research findings are therefore more meaningful if plant needs are also considered. For this reason a brief review of this related application is deemed useful.

Many researches have been published on the subject of measuring porosity and pore-size distribution and their importance to plant growth. Albeit, many refer to threshold bulk density rather than to pore volume or pore-size distribution.

Edwards et al. (18) have shown that a discrete ped bulk density of about 1.8 g/cc is the threshold above which peds are not penetrated by corn roots in Planosol. They also indicated that the minimum intra-ped porosity of peds penetrated by roots was about 33 percent. Veihmeyer and Hendrickson (40) found that sunflower roots did not penetrate sands having bulk densities greater than 1.75 g/cc nor clays having bulk densities greater than 1.46 to 1.63 g/cc.

Taylor and Gardner (39), on the other hand, suggested that soil strength rather than soil bulk density was the critical impedance factor controlling root penetration of cotton seedlings in sandy soils. Wiersum (42) and Aubertin and Kardos (4) demonstrated the effect of rigidity of the pore structure on root penetration. Aubertin and Kardos found, for example, that maize roots did not penetrate into rigid porous systems with pore diameters smaller than approximately 138μ. However, roots were found to grow approximately the same in all non-rigid systems regardless of the size of the pores.

There is a large body of literature that shows that soil porosities based on bulk soil volume of less than 10-15 percent will reduce plant growth (27).

Soil Aggregates as Porous Materials

Soil aggregates consist of various minerals and organic matter associated into an agglomerate that is quasi stable to mechanical or hydration force imposed upon them. These domains hold together by attractive forces between minerals and between minerals and organic matter posses pores. There are also spaces between aggregates that form a connecting system of voids. There are thus intraaggregate and interaggregate pores (13,35).

Larson (23) mentioned that secondary aggregate size and compacting pressure around the seedling root could influence the total porosity and the size of interaggregate and intraaggregate pores. The size of the interaggregate and intraaggregate pores, in turn, influence water storage and movement in the soil.

Currie (13) suggests that interaggregate porosity can be used as a measure of cultivation state, whereas intraaggregate porosity is a measure of structural state. Cultivation tends to alter the relative dispositions of existing clods and crumbs thereby altering the interaggregate air voids, whereas the practice of soil management alters the separation of primary particles causing a change of voids within the aggregates, that is, in structure.

Characteristics of Pore System in Soils

The extent to which primary soil particles are grouped to form larger aggregates is a complex function of numerous variables. Agents affecting the formation of soil aggregates apparently include: (a) size distribution of primary soil particles, (b) amount of clay, as well as types of clay minerals present and (c) organic polymers. These factors are all involved in the formation of aggregates and the pore characteristics.

Data presented by Tamboli *et al*, (38) on aggregates 3.0 to 0.5 mm diameter indicated that larger aggregates had higher water contents at low suctions (0.1 and 1.0 bar) than did small ones. This difference became insignificant at suctions equal to or larger than 10 bars. They assumed that the greater intraaggregate porosity of the larger aggregates was the dominant factor determining the difference in water content and that there was a possible textural heterogeneity between small and large aggregates. Amemiya (2) also showed the same result. But he explained that the differences in water content at low suction were due to changes in total air voids.

Curris (13) found that aggregate porosity increased as aggregate size increased. When aggregate size increased from 0.5-1 to 1-2 mm, aggregate porosities increased from 0.392 to 0.442 for highfield, permanent pasture and from 0.281 to 0.301 for barnfield, unmanured plot. He ignited both soils at 800°C for this comparison. He reasoned mathematically that these results were predictable. Voorhees *et al*. (41) also show that specific aggregate pore volume, cc/g, increased as aggregate size increased whether soil was air-dried or at 0.10 bar suction. But they made no attempt to explain this. From aggregate size of 2-3 to 5-10 mm, a 11 percent increase of specific aggregate pore volume existed for Aastad aggregates and 6 percent for Mitchell aggregates in an air-dried state.

Effect of aggregate size on total porosity is quite another matter. Baver (5) cited Doiarenko's work that total porosity fell to about 24 percent as the size of soil granules decreased from 5.0 to $<$ 0.5 mm. Non-capillary porosity increased and capillary porosity decreased as aggregate size increased from $<$0.5 to 3-5 mm. On the other hand, Larson (23) indicated that as aggregate size decreased the total porosity increased and the size of the pore decreased.

Methods of Measuring Soil Porosity and Pore-Size Distribution

Several methods have been used to determine the porosity of discrete dry soil structural units. Though each method has its particular procedure, methods can be grouped into three categories: displacement by non-polar liquid or by fine powder, mercury intrusion and thin sectioning.

Displacement Methods

Soil porosity has been determined by many investigators using a non-polar liquid to displace the air in the porous aggregates. Various kinds of liquid have been recommended. Russell (31) determined the volume of clods by measuring their displacement in water after the clods had been coated with paraffin. Smith (33) found that the displacement with Narsol, a non-polar liquid, was especially convenient with heavy clay soils from which satisfactory undistrubed soil cores could not be obtained. Other variation have been reported (28,32). Chepil (10) measured apparent density of aggregates by air elutriation, and considered it the most suitable method for estimating the density of soil crumbs less than 6 mm in diameter. A recent study by Currie (13) has shown a relation between interaggregate and intraaggregate porosity by using kerosene as a displacing agent. Voorhees *et al*. (41) utilized glassbead displacement to determine the specific pore volume of soil aggregates for both dried and moistened soil aggregates. The specific pore volume of an aggregate was thus calculated by knowing the aggregate and fabric densities.

Hg-Porosimetry

By forcing mercury into porous materials under continuously increasing pressure, one can measure the total porosity and pore-size distribution within a substance (16, 19, 30, 43). This method is especially suited for determining the distribution of pore size greater than 0.01μ.

Thin Sectioning

Detailed explanation for making thin sections are given in many articles (9, 15, 26). The soil sample is subjected to an absolute pressure of about 2 cm Hg. An embedding medium with a refractive index approximating that of the principal minerals present in the sample is poured onto the sample and allowed to penetrate and in time to polymerize into a solid, thus fixing the fabric structure. The specimen is then cut, mounted to a glass slide and a thin section is cut. The section is ground and polished to a thickness of about 30μ. Under polarized light, one can easily distinguish soil from pores. Using a special eyepiece-mounted grid one counts a statistical number of hits or misses and thus calculates porosity.

Measurement of Pore-Size Distribution

The extensive investigations of Brutsaert (8), Childs (11), Leamer and Lutz (25), and Smith *et al*. (34) demonstrated that the nature of a pore system in soil can be deduced from its moisture characteristic curve. Having an experimentally obtained moisture suction curve, one can, by means of the well known capillary equation $r = 2t/dgh$, easily deduce a cumulative pore-size distribution by assuming cos i (where i is the wetting angle) is 1.0.

Fong and Browning (20) found that a differential curve derived from the moisture characteristic curve is a useful technique to show the relationship between aggregate stability, the pore size in which non-capillary water is stored and the distribution of the total air voids. A soil with a high peak value of dV/dP in a plot of dV/dP versus P indicated a high amount of a particular size of pore and a high value of aggregate stability. Bendixen and Slater (6), however, have found that the length of time allowed for drainage is also closely correlated to the pore system that it may also be used to give an integrated weighting to pore size classes.

During wetting and drying cycles, the phenomena of swelling and of shrinkage are always occurring in soil. It is necessary to take this into account if the moisture characteristic curve is used in evaluating the size distribution of voids. Quirk and Panabokke (29) found that 70 percent or more of the swelling took place at or below pF 3 during the wetting process. Lauritzen and Stewart (24), on the other hand, found that the wilting percentage, presumably pF 4.2, coincided with the moisture content at which maximum shrinkage occurred during drying of the soil.

MATERIALS AND METHODS

Soil Materials

Soils used for these experiments were chosen in order to find out the relation between aggregate porosity and soil type. Samples from six soil types, A_p horizon, were taken in May 1966 from locations shown in figure 1. Aastad loam and Bearden silty clay loam, which are classified as Chernozem and $CaCO_3$ solonchak respectively, are located in western Minnesota. The other soils were obtained from southeastern Minnesota. Clarion clay loam and Hayden silt loam are till-derived and Fayette silt loam and Tama silt loam are formed on loessial materials.

Samples from adjacent cultivated and virgin areas were collected for each soil type. The term virgin used here indicated the soil had been undisturbed for as long as local residents remembered without being plowed and cropped. This is probably more than 30-40 years as a minimum. Cultivated soils were taken from corn fields.

After three days drying in the laboratory at room temperature, naturally occurring soil aggregates were sieved into four sizes: 0.5-1, 1-3, 3-5, and 5-8 mm. A subsample of each of the original 12 air-dried soils, either virgin or cultivated, was mechanically pulverized to pass a 0.3 mm sieve, was thoroughly mixed and wetted by fine mist spray to about 0.3 bar of water suction. Moist soil was aged 24 hours, pressed under a thin rubber membrane at 50 psi pressure for 2 minutes. The briquet thus formed was crushed gently by hand and separated by sieving into the four size groups as above. They were then air dried, and designated as artificial aggregates. Plant residues and stones which could be seen by the naked eye were removed from all aggregate samples.

Six soil types, two cropping histories, each of natural and artificial aggregates and all in four size classes gave a total of 96 samples. Characteristics of the soils are shown in table 1.

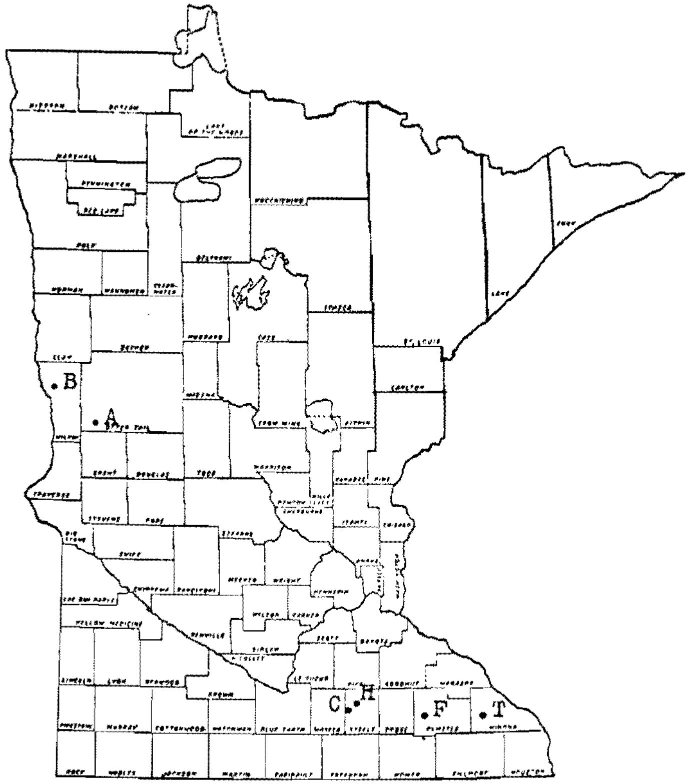

Figure 1. Location of Soil Samples in Minnesota

A.	Aastad 1	SW¼ of NW¼ Sec 26 T131N R44W
B.	Bearden si cl 1	NW¼ of NW¼ Sec 22 T135N R48W
C.	Clarion cl 1	NW¼ of NW¼ Sec 23 T107N R21W
F.	Fayette si 1	SW¼ of NW¼ Sec 7 T106N R14W
H.	Hayden si 1	SW¼ of NW¼ Sec 21 T107N R20W
T.	Tama si 1	NW¼ of SW¼ Sec 33 T106N R9W

Table 1. Some Selected Properties of Soil Aggregates.

Soil Type	Condition	O.M	pH (paste)	Texture > 50µ	Texture 2-50µ	Texture < 2µ
		Percent		Percent		
Aastad	Virgin	7.2	6.93	36.6	40.7	22.7
	Cultivated	4.6	6.82	43.6	32.5	23.9
Bearden	Virgin	7.0	7.37	19.5	54.8	26.7
	Cultivated	3.4	7.54	26.1	48.9	25.0
Clarion	Virgin	5.1	6.62	24.8	45.1	30.1
	Cultivated	4.0	6.19	39.6	31.9	28.5
Fayette	Virgin	6.4	6.41	8.0	76.0	16.0
	Cultivated	1.7	7.05	14.8	68.1	17.1
Hayden	Virgin	2.4	5.10	43.5	45.7	10.8
	Cultivated	1.4	7.38	63.2	28.5	8.3
Tama	Virgin	6.3	7.20	6.1	70.9	23.0
	Cultivated	3.0	7.13	5.6	71.0	23.4

Experimental Design

A split-split-plot design was used in this experiment from which the effect of soil type, condition (virgin vs cultivated), treatment (natural vs artificial) and aggregate size were all taken into account (12,36).

Hg-Porosimetry

Twenty four out of the 96 samples were sent to American Instrument Co. Inc. Analytical Laboratory in Maryland for Hg-porosimetry analysis. The applied pressure in the analysis ranged from 6 to 15,000 psi corresponding to pore diameters of 17 to 0.012µ respectively. Total porosity and pore-size distribution of pores 17-0.012µ were obtained. The procedure they used in the analysis is described in an article by Drake and Ritter (17).

The Aminco-Winslow porosimeter operates on the mercury intrusion principle whereby samples, either solid or powdered, are immersed in mercury and subjected to increasing pressure. The amount of mercury forced into the pore of the material under test is measured at specific intervals. Pressure and volumetric readings are plotted on semi-log graph paper from which pore diameter and intrusion data can be extracted directly. The distribution curve is limited to the pore diameter range mentioned above. If the particle and bulk densities of the test sample are known, total porosity and porosity due to pores above and below the operating limits of the porosimeter can also be computed.

Glassbead Displacement

The glassbead displacement method mainly followed the procedure described by Voorhees et al. (41). The particle density of aggregates was measured with 5 grams of soil aggregates and a 25 ml pycnometer by the procedure in ASA Methods of Soil Analysis (7). The fabric density of aggregate, D_f, was calculated according to:

$$D_f = \frac{D_w(W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)} \quad \text{g/cc}$$

where W_a = weight of pycnometer

W_s = weight of pycnometer with soil

W_{sw} = weight of pycnometer with soil and air-free water

W_w = weight of pycnometer with air-free water

D_w = density of water at that temperature

As long as fabric density of aggregates is known, the aggregate density or apparent density can be computed. A known weight of 10 to 15 grams air-dried aggregates were mixed with about 40 ml of 38μ diameter glassbeads in a 50 ml plastic cylinder. Uniform packing was obtained by tapping the sides of the cylinder 30 seconds with a vibrating marking pen at approximately 100 vibrations/second. Additional beads were added to the cylinder and the cylinder was tapped again for 30 seconds. A third addition of beads was made accompanied again by 30 seconds tapping. Finally the cylinder was overfilled and excess beads were removed with a straight-edge. The aggregate-bead mixture was weighed and the specific pore volume of the air-dried aggregates, P_a, was computed as follows:

$$P_a = (V_c - \frac{W_b}{BD_b})W_a^{-1} - D_f^{-1} = D_a^{-1} - D_f^{-1} \qquad cc/g$$

Where V_c = volume of cylinder, 50 ml

W_b = weight of bead-aggregate mixture minus weight of aggregates

BD_b = obtained from packing glassbead alone under conditions similar to the packing of the bead-aggregate mixture

W_a = weight of air-dried aggregates

D_a = aggregate density

D_f = fabric density

In order to reduce variation and thus assure the accuracy of the specific pore volume, eight replications of D_a were made for each soil sample. By multiplying the specific pore volume by the aggregate density the aggregate porosity was obtained.

Thin Sectioning

The most sensitive part of the procedure for preparing thin sections is the impregnation process prior to thin sectioning. Air-dried aggregates in an aluminum dish were placed in one of the two interconnected vacuum chambers. The embedding material composed of a mixture of 600 ml Vostopal H, 500 ml monostyrene, 0.7 ml cobalt naphthenate and 1.4 ml cyclohexane peroxide was located in the other chamber. Pressure in the two chambers was lowered with a water pump at a pressure of about 2 cm Hg. A valve on the connecting tube was closed and the pressure in the sample chamber was reduced a few mm more. The reduced pressure was held for 30 minutes. A valve on a second connecting tube was open and the impregnating material was allowed to flow slowly into the sample container, flow being induced by the pressure difference between the two chambers. The sample was kept under vacuum overnight.

Polymerization and hardening proceeded at room temperature for about two weeks. The hardened block was cut into a rectangular segment 2 cm x 2 cm x 1 cm using a coarse diamond saw. One of the 2 cm x 2 cm sides

of this segment was then ground sequentially on 240, 400, and 600 grit silicon carbide paper. The finished side was cemented to a glass slide with a mixture of 20 ml Vestopal H, 0.3 cyclohexene peroxide and 0.15 ml cobalt naphthenate and pressure with the fingers. About 2 days was necessary for hardening. The glass slide with the attached sample was mounted on a diamond saw and the sample was cut to a thickness of 0.5 to 1 mm. It was then ground on 240, 400 and 600 grit silicon carbide paper to a thickness of approximately 30μ.

Under a polarized microscope the color of quartz changes with the thickness of quartz. When the thickness of quartz becomes 40 to 50μ it appears yellow and at about 30μ thickness it is colorless (22). Since soil is composed of a great amount of quartz the color change of quartz mineral can be used as an index of thickness of the thin section.

The prepared slides were observed at 400 magnification with a polarizing microscope. Under birefringence it is possible to distinguish between mineral particles and voids, the latter being filled with the binding material. Since the binding material does not show double refraction, the voids remain dark under crossed nicols. Thus it was possible to differentiate between mineral particles and air voids. Intraaggregate porosity was determined by observing 8 fields of sample aggregates with a special eyepiece having 25 marked points. By counting how many points fell upon pore spaces aggregate porosity was simply the ratio of numbers of points hitting voids to total numbers, 25. Interaggregate pores were not included. The Zeiss Integrating Eyepiece I used is illustrated in figure 2. Possible errors in the method are discussed in the section on results and discussion.

TERMINOLOGY

Soil porosity is expressed by the ratio of all voids to the total volume of soil. For an air-dried soil the volume of water is negligible. Soil voids simply consist of air voids. In a volume element of soil both intraaggregate and interaggregate porosities are important. When a discrete aggregate is used as a unit only intraaggregate porosity can be evaluated.

The data obtained in this investigation refer merely to intraaggregate porosity. In the ensuing discussion the term of aggregate porosity is synonymous with intraaggregate porosity.

Aggregate porosity can be computed either as the ratio of voids within aggregate to volume of the aggregate or as the ratio of volume to total soil volume. Their relationships are shown as follows:

$$v_{va} = \frac{V_v}{V_a} = P_a \times D_a \quad ; \quad v_{vs} = \frac{V_v}{V_s} = P_a \times D_b$$

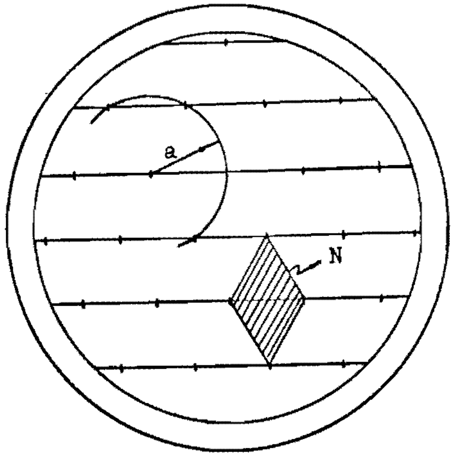

Figure 2. Zeiss Integrating Eyepiece I with Network of 25 points. Internal distance between points = a. The area appointed to each point, i.e., the network is

$$N = \sqrt{3}\, a^2/2$$

Total area encompassed by the circle is 25N (21).

$$v_{vb} = \frac{V_{vb}}{V_s} \quad ; \quad V_a + V_{vb} = V_s$$

where v_{va} = aggregate porosity, based on aggregate volume

v_{vs} = aggregate porosity, based on bulk soil volume

v_{vb} = interaggregate porosity, based on bulk soil volume

V_v = voids within aggregates

V_a = volume of aggregates, including V_v

V_s = bulk soil volume (total soil volume)

V_{vb} = voids between aggregates

P_a = specific pore volume, cc/g

D_a = aggregate density

D_b = bulk density of soil

The relationship between v_{va} and v_{vs} is

$$v_{vs} = v_{va}\,(1 - v_{vb})$$

and total poposity

$$v_t = v_{vs} + v_{vb} = v_{va}\,(1 - v_{vb}) + v_{vb}$$

A similar equation was derived by Currie (13). But what the author call aggregate porosity, he calls crumb porosity. It should be clearly noted that aggregate porosity obtained from these experiments is v_{va} but not v_{vs}. The latter is much smaller than the former. Aggregate porosity, v_{va}, is calculated by multiplying experimental values of specific pore volume, P_a, with aggregate density, D_a.

RESULTS AND DISCUSSION

Effect of Aggregate Size on Aggregate Porosity

Aggregate porosity was measured on 96 samples in which individual aggregates varied in diameter from 0.5 to 8 mm in four size classes. The results are shown in table 2. Analyses of variance are shown in table 3.

Aggregate porosity, v_{va}, was shown to vary with aggregate size at the 1 percent level for both glassbead displacement and thin section methods.

Table 2. Average Values of Aggregate Porosities From Two Methods, Under Each Method Two Treatments and Two Conditions Were Included.

Soil Type	Aggregate Size, mm			
	0.5-1	1-3	3-5	5-8
Aastad	.335	.334	.353	.372
Bearden	.297	.319	.332	.343
Clarion	.302	.310	.324	.352
Fayette	.383	.380	.398	.403
Hayden	.304	.332	.339	.364
Tama	.351	.361	.373	.388

Porosity values averaged from two methods showed that aggregate porosity, v_{va}, increased at least 5.2 percent for Fayette soil and at most 19.7 percent for Hayden soil as aggregate size changed from 0.5-1 to 5-8 mm. According to results of Voorhees et al. (41), aggregate porosity increased 8 percent for Aastad aggregates and 4 percent for Mitchell aggregates as aggregate size increased from 2-3 to 5-10 mm.

Currie (13) predicted the change of aggregate porosity with aggregate size based on surface area effects. Using an Oso Flaco fine sand as an example, he found that aggregate porosity increased as aggregate size increased. A comparison of his theoretically calculated values with experimental results is shown in figure 3.

The slope for aggregate porosity versus aggregate size was in the order of 10^{-3}/mm. Currie's calculated slope from the simple equation was the lowest, results of this experiment showing values two - to four-fold greater. Data obtained from Voorhees et al. (41) had intermediate values of slope.

Table 3. Analyses of Variance for the Data From both Glassbead Displacement and Thin Section Methods.

Source of Variance	Degree of Freedom	F_{GD}	F_{TS}
Soil Type	5	1.47 NS	2.56 NS
Condition	1	7.68 *	15.37 **
Error (E_a)	5		
Treatment	1	11.93 **	0.18 NS
Trt x Condition	1	0.64 NS	2.38 NS
Error (E_b)	10		
Size	3	4.89 **	38.90 **
Size x Condition	3	0.24 NS	0.73 NS
Size x Trt	3	1.42 NS	0.78 NS
Size x Trt x Condition	3	0.20 NS	0.10 NS
Error (E_c)	60		
Total	95		

Condition	virgin soil vs cultivated soil
Treatment	natural aggregates vs artificial aggregates
F_{GD}	F values from glassbead displacement method
F_{TS}	F values from thin section method
NS	Not significant
**	Significant a 1 percent level
*	Significant at 5 percent level

There is, of course, some question of the validity of comparing slopes in different ranges of porosity. No data, virtually, have yet been presented which might be compared to Currie's postulated relationship. Neither data from Voorhees et al. nor from this thesis furnish a definite critique of Currie's calculation, however, the comparison is given for what value it may serve in suggesting future study.

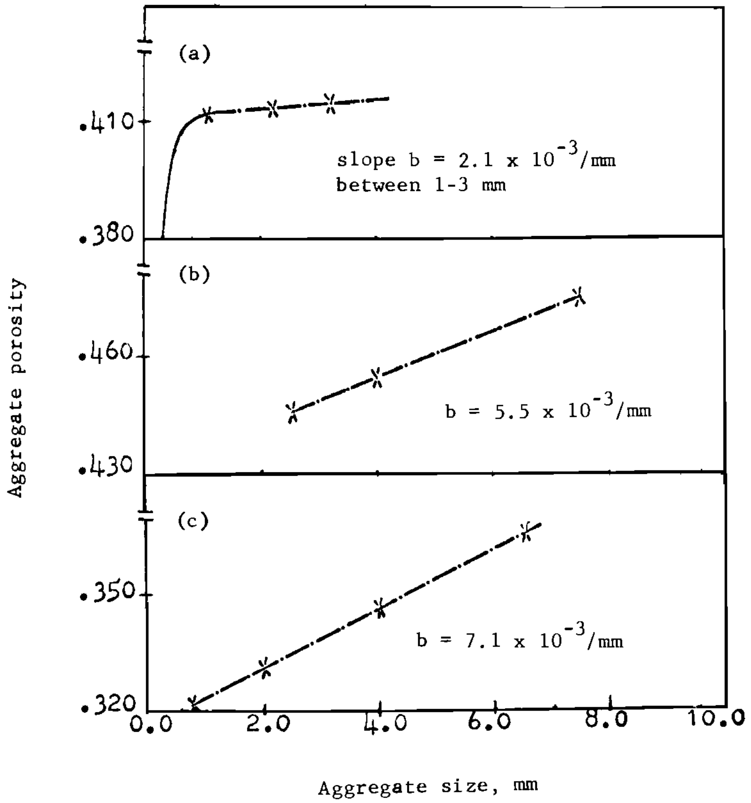

Figure 3. Regression line of Aggregate Porosity, v_{va}, on Aggregate Size. (a) Currie's calculated data (13). (b) Experimental result from Voorhees et al (41). Individual slope varied from 3.87 x 10^{-3}/mm for Mitchell aggregates to 7.06 x 10^{-3}/mm for Aastad aggregates. (c) Data corresponding to Table 2 in this thesis. Individual slopes for Aastad through Tama were 5.34, 7.58, 11.1, 6.37, 11.1, and 6.42 x 10^{-3}/mm respectively.

Currie (14) explains that on a unit volume basis as aggregate size decreases a fraction of the intraaggregate pores gradually disappears in favor of interaggregate pores for two reasons: (a) aggregate edge pores, ineffective as intraaggregate pores, increase per unit volume, and (b) pores with diameters larger than the aggregates disappear. Consequently, aggregate porosity may therefore be a function of aggregate size when textural composition of aggregates is constant.

Table 4. Organic Matter and Clay Contents in Cultivated, Natural Soils for Each Soil Type and Each Aggregate Size.

Soil Type	Soil Properties	Aggregate Size, mm			
		0.5-1	1-3	3-5	5-8
		Percent			
Aastad	O.M.	4.6	4.4	4.8	4.6
	Clay	23.9	24.7	23.6	23.5
Bearden	O.M.	3.6	3.3	3.4	3.3
	Clay	25.0	25.3	24.6	25.0
Clarion	O.M.	3.9	4.1	3.8	4.1
	Clay	30.2	29.4	27.9	26.7
Fayette	O.M.	1.8	1.8	1.5	1.5
	Clay	17.2	19.5	16.2	15.6
Hayden	O.M.	1.4	1.4	1.4	1.5
	Clay	7.2	10.2	7.2	8.5
Tama	O.M.	2.9	2.8	3.2	3.0
	Clay	23.6	21.3	25.5	23.0

Organic matter and clay contents for various aggregate sizes are shown in table 4. There is no indication that either organic matter or clay content increased as aggregate size decreased. Even though aggregate porosity is higher for Fayette and Tama soils, neither clay content nor organic matter can account for these differences. Other investigators (3,38) have raised the question whether texture is always constant with aggregate size.

Effect of Soil Type on Aggregate Porosity

The effect of soil type on aggregate porosity is shown in table 2 and figure 4. Soils from loess, Fayette and Tama series, show the highest aggregate porosities while till-derived soils, Clarion and Hayden series, have relatively low values. Aastad and Bearden soils have intermediate ones.

Strickling (37) mentioned that soil aggregate porosity was found to be closely related to soil texture and organic matter. He found that organic matter and silt content tended to increase porosity.

The process of formation of a soil on till is quite different than on loess. Till is a non-stratified heterogenous mixture of mineral materials, while loess is composed of silty parent materials deposited by wind. Textural and related physical properties result in considerable differences in weathering and thus in morphology of the soil profiles developed on them.

When silt content and aggregate porosity are compared for each soil type from tables 1 and 2, the high aggregate porosities for Fayette and Tama series seems correlated with the extremely high content of silt and low content of sand. The effect of organic matter is not clear since there was no direct relation observed in any of the soil type comparisons.

Analyses of variance did not show that aggregate porosity was significantly dependent on the soil type for either method (table 3). Yet as the previous discussion shows, one would expect a difference to exist. Aside from the possibility that the expectation was countermanded in a real way, there are two possible reasons significance was not found. The use of soil types as replicates in the split-split-plot design gave an error term with few degrees of freedom. Secondly, the cultivated soil with small aggregate porosity differences decreased the sensitivity of the overall mean from virgin and cultivated soils. Analyses on the virgin soils alone left little basis for a valid F-test.

Aggregate Porosity of Virgin and Cultivated Soils

Data in table 5 indicate all the virgin soils have higher aggregate porosities than the cultivated soils. Analyses of variance (table 3) shows the difference in aggregate porosity between virgin and cultivated soils is significant at the 5 percent level for glassbead displacement method and 1 percent level for thin section method.

The order of reduction of aggregate porosity by cropping (virgin to cultivated soil) was Fayette > Tama > Hayden > Aastad > Bearden > Clarion based on an average value of the two methods. Apparently, porosity differences between virgin and cultivated soils are also higher for loess-derived soils and lower for till-derived soils.

Aggregate porosity seems to be more closely related to aggregate bulk density than to either organic matter or clay content. Aggregate bulk density is a function of at least three variables, namely organic matter content, texture and degree of packing. Yet there is no clear

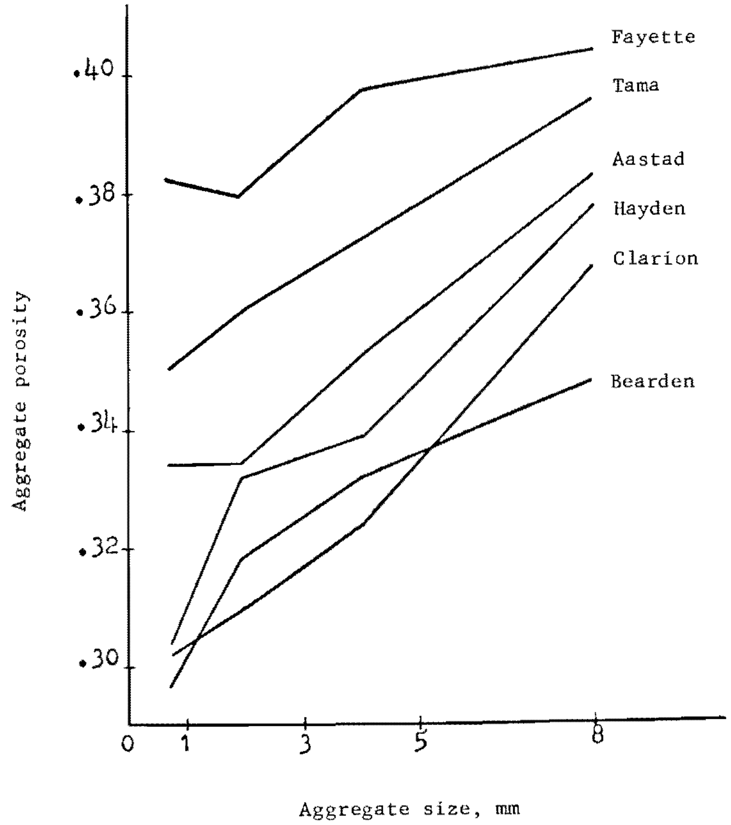

Figure 4. Aggregate Porosity as a Function of Aggregate Size (Data from Table 2)

cut relationship between the first two of these and aggregate porosity. This is affirmed if one compares Clarion and Hayden series. The Clarion soil with a relatively higher content of organic matter and clay had an almost equivalent aggregate porosity to Hayden with its very low organic matter and clay contents.

The thing that stands in sharp focus is the fact that virgin soil has a higher porosity than cultivated for any soil type.

Table 5. Comparison of Aggregate Porosity for the Natural Aggregates Between Virgin and Cultivated Soils. Values are Averages for Four Different Sizes.

Soil Type	Condi-tion	O.M.	Clay	D_a	Aggregate Porosity	
					GD	TS
		Percent	Percent	g/cc	Percent	
Aastad	V	7.2	22.7	1.49	.372	.390
	C	4.6	23.9	1.63	.328	.343
Bearden	V	7.0	26.7	1.58	.329	.344
	C	3.4	25.0	1.69	.303	.318
Clarion	V	5.1	30.1	1.66	.311	.350
	C	4.0	28.5	1.68	.316	.308
Fayette	V	6.4	16.0	1.35	.475	.439
	C	1.7	17.1	1.60	.339	.343
Hayden	V	2.4	10.8	1.56	.389	.332
	C	1.4	8.3	1.78	.310	.308
Tama	V	6.3	23.0	1.40	.440	.404
	C	3.0	23.4	1.58	.346	.314

Condition Virgin soil vs cultivated soil
GD Glassbead displacement method
TS Thin section method
D_a Aggregate density

Aggregate Porosity of Natural and Artificial Aggregates

In laboratory research there is interest in forming artificial aggregates to study various phases of the stabilization process and the mechanics involved in it. A procedure in the University of Minnesota Soil Physics Laboratory is to press pulverized, moistened soil into a briquet and to mechanically break it into small parts and separate into the desired size limits by sieving. A pressure of 3.5 kg/cm^2 was arbitrarily chosen to approximate pressures that could be expected under machines used in field soils (1). It was considered desirable to compare porosities of these artificially produced aggregates with naturally occurring ones. Data are shown in Table 6.

Table 6. Comparison of Aggregate Porosities Between Natural and Artificial Aggregates, Average Values from Four Different Sizes of Aggregates.

Soil Type	Method	Virgin		Cultivated	
		Nat	Art	Nat	Art
Aastad	GD	.372	.347	.328	.325
	TS	.390	.353	.343	.328
Bearden	GD	.329	.320	.303	.276
	TS	.344	.335	.318	.358
Clarion	GD	.311	.310	.316	.324
	TS	.350	.352	.308	.305
Fayette	GD	.475	.469	.339	.301
	TS	.439	.415	.343	.347
Hayden	GD	.389	.380	.310	.299
	TS	.332	.355	.308	.307
Tama	GD	.440	.424	.346	.312
	TS	.404	.378	.314	.331

GD Glassbead displacement method
TS Thin section method
Nat Natural aggregates
Art Artificial aggregates

Porosity of natural aggregates was significantly higher than that of artificial aggregates at the 1 percent level for glassbead displacement method but not significantly different for the thin section method (table 3).

There were, of course, two kinds of natural aggregates: those occurring under natural vegetation and those from cultivated fields. Table 6 shows the porosities of these two aggregate sources.

Aggregate porosities of virgin soils were reduced considerably if pulverized and reformed by pressing. In contrast those of cultivated soils were reduced little when reformed. Presumably in cultivated soils aggregates formed under forces of tillage tools and implements are more nearly the porosity of those formed by laboratory pressures.

The glassbead displacement method showed natural aggregates had a higher aggregate porosity than artificial ones for either virgin soil or cultivated soil. The thin section method did not show significant differences between porosities of artificial and natural aggregates.

Comparison of Glassbead Displacement and Thin Section Methods for Determining Aggregate Porosity

A Comparison of the two methods was made by plotting porosities determined by one against those determined by the other. This is shown in figure 5.

Though all values were nearly equally distributed on both sides of the diagonal, aggregate porosity obtained by glassbead displacement method was relatively low at lower values and relatively high at higher values of porosity.

There are inherent errors in determining aggregate porosity by each of the methods used. The thin section method gives a statistically precise value only if a near infinite number of points is counted and if there are assumed to be no pores of length less than the thickness of the section (30 microns in this case).

Precision in the thin section method is based on at least three assumptions. First, it is statistically precise if a very large number of points is counted. Second, failure to count hits or misses correctly on the 25 points in the network of the Integrating Eyepiece I is a possibility in so tedious a work. An 8 percent error is provided if one hit is mistaken in counting a field. Third, if there are pores that do not traverse the thickness of the section, then they may not be observable and therefore not counted. Assuming one can observe and count a pore that traverses 1/2 the slide thickness of 30 microns, and assuming a pore diameter that approaches zero and a minimum length of 24 microns, we can calculate that if randomly oriented about 75 percent of the pores with diameters less than 15 microns will be counted. All pores $>15\mu$ diameters will, of course, be counted, but as will be observed later, a large proportion have diameters $<15\mu$. As pore dimensions approach an isometric shape, a higher percentage of the $<15\mu$ diameter pores will go uncounted.

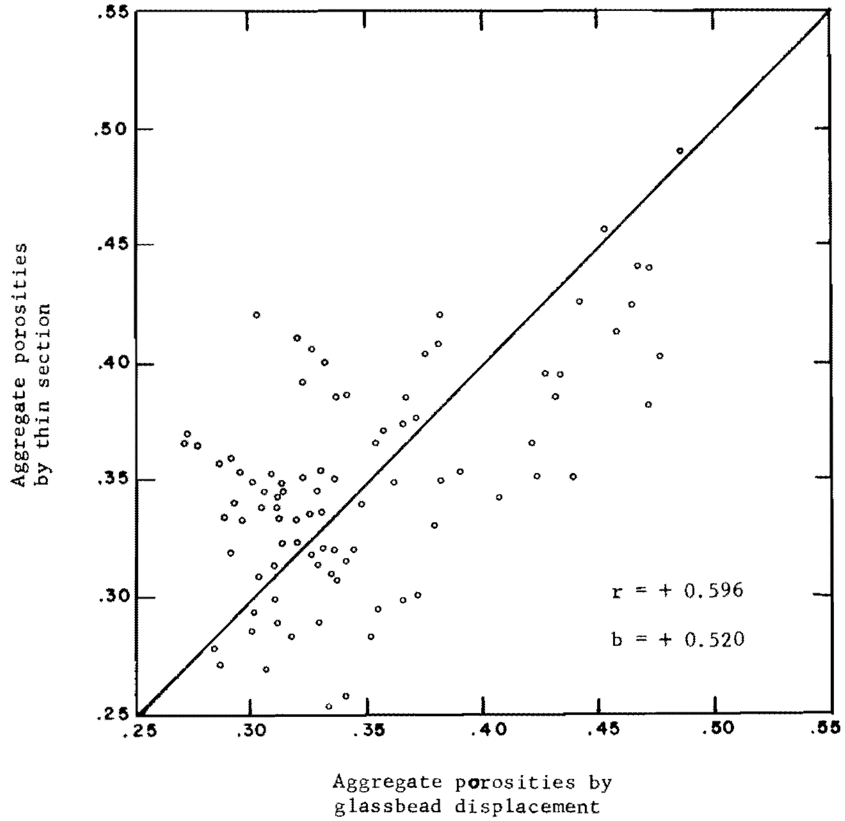

Figure 5. Comparison of Aggregate Porosities Obtained from 96 Samples from Thin Section and Glass Bead Displacement Methods

There are also known errors in the glassbead displacement method. It was observed microscopically that there was more or less penetration of 38μ glassbeads into aggregate surfaces. If part of the air voids within aggregates was displaced by glassbeads the computed aggregate porosity would then be reduced by this fraction. No attempt was made to assess the magnitude of this error. Aggregate porosity would be reduced to a greater extent in small aggregates than in large ones because of their greater surface, but the extent to which this would be counterbalanced by the existence of large pores in large aggregates is unknown.

Precision of the glassbead displacement method may be slightly better than that of the thin section method for the number of measurements made by each method. The standard error for 8 measurements on 96 samples for the glassbead displacement method varied from 0.001 to 0.008 and for counting 8 x 25 points by the thin section method from 0.007 to 0.034. However, a matched-pairs t-test showed that there was actually no difference between the two methods in the statistical means.

Consider figure 5 again. Aggregate porosities by glassbead displacement method were relatively larger than those from thin section method at high porosities. But this difference became insignificant when aggregate size was small. In this case penetration of glassbeads into the greater amount of exposed pores gave an error nearly equal to the thin section method and thus nearer coincidence of data from the two methods.

The preceding statements of comparison between the methods apply, of course, only to the number of measurements made. Statistical accuracy could be improved by additional measurements. Errors due to glassbead penetration or to discontinuity of pores or small pores in the thin section method would remain.

Each of the two methods for determining porosity has its advantages for particular studies. Shape of pores, for example, can be studied by thin section though not by glassbead displacement method.

There is a practical consideration in comparing the two methods namely time and ease of measurement. When the experimental procedure were taken into account, the glassbead displacement method is much less time consuming. The only equipment needed for the glassbead displacement method is a four-digit balance and vibrator. The thin section method, on the other hand, requires a polarized microscope, coarse and fine saw, vacuum chamber and polishing machine. Elapsed time to prepare thin sections is also much greater. Three weeks are required for completing the embedding and hardening of aggregates in a thin section. Furthermore, grinding, polishing and counting are a time consuming and laborious for the thin section method.

Pore-Size Distribution

By forcing mercury into aggregates, both specific pore volume and pore-size distribution were measurable. Pore diameters measured ranged from 0.012 to 17μ. Specific pore volumes are listed in table 7. Also listed are the specific pore volumes by the glassbead displacement and thin section methods obtained by dividing aggregate porosity by aggregate density, i.e.,

$P_a = v_{va} \times D_a$.

Specific pore volume measured from the Hg-porosimeter are considerably smaller than those from either the thin section or glassbead displacement methods. There are at least two possible reasons for this. Mercury intrusion measurements began at 17μ pores. Larger pores and some extremely small ones were omitted. Furthermore, an unknown amount of deformation of the friable soil aggregates may have occurred under pressure as high as 15,000 psi used in the test. The low values of specific pore volumes for the Hg-porosimeter are thus not unexpected and in fact should not be comparable to those of the other methods.

Table 7. Specific Pore Volume, cc/g, for Artificial Aggregates of 3-5 mm Diameter.

Soil Type	Condition	Specific pore volume, cc/g		
		GD	TS	Hg-porosimetry
Aastad	Virgin	.235	.245	.188
	Cultivated	.206	.197	.152
Bearden	Virgin	.192	.212	.173
	Cultivated	.155	.210	.157
Clarion	Virgin	.189	.208	.146
	Cultivated	.198	.190	.127
Fayette	Virgin	.330	.313	.272
	Cultivated	.168	.197	.171
Hayden	Virgin	.241	.221	.217
	Cultivated	.167	.163	.139
Tama	Virgin	.295	.274	.244
	Cultivated	.181	.205	.172

GD Glassbead displacement method
TS Thin section method

Pore-size distribution curves from the Hg-porosimeter are shown in figure 6. Almost 91 to 92 percent of the pore volume was contributed by pores greater than 0.2μ diameter. Pores of this diameter will support a pressure differential of 15 bars when wetted with water and placed on a suitable membrane. Water-wetted soil with pores 17μ diameter will support a pressure differential of about 0.16 bar suction. A wetting angle of zero is assumed in both cases.

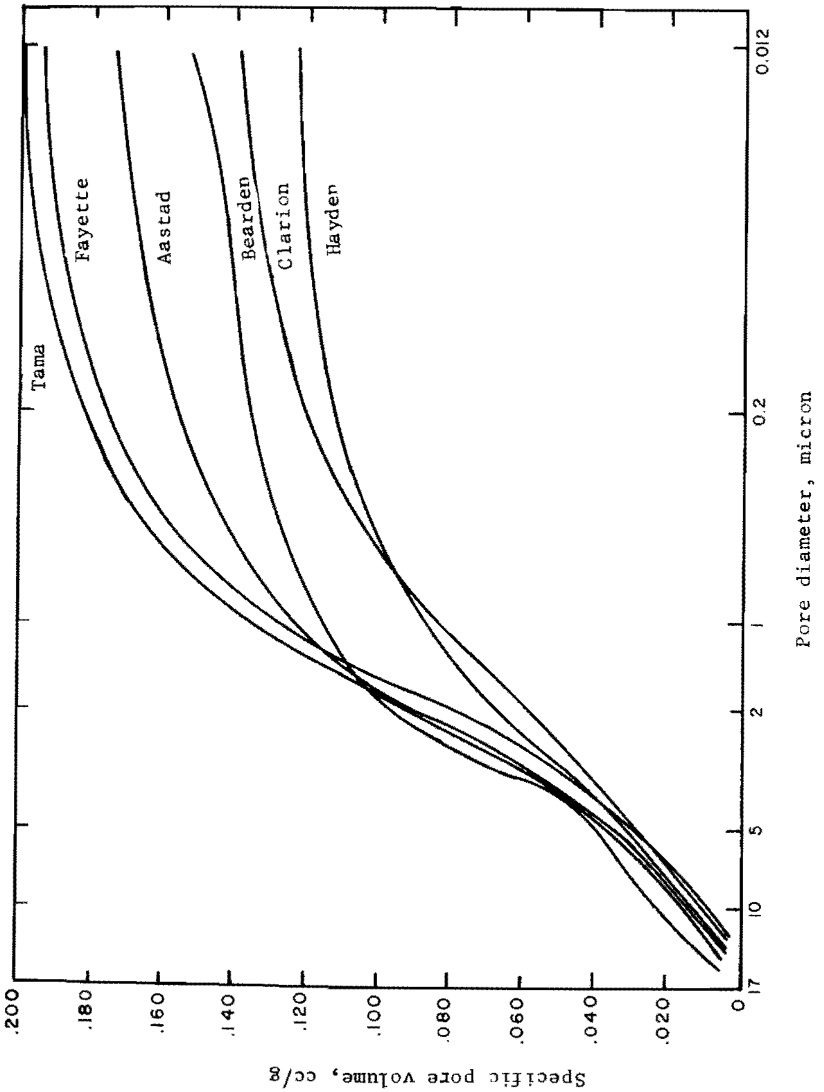

Figure 6. Pore-Size Distribution for Cultivated, Natural Aggregates with Size of 3-5 mm from Hg-porosimeter

The higher pore volume of Fatette and Tama series over Hayden and Clarion soils was due to their higher proportion of larger pores. The greater rate of change of slope occurred at pore diameters between 1 and 5 microns.

In order to find out the ratio of aggregate porosity to total porosity based on the bulk volume, bulk density of soil aggregates was measured by gently tapping a container of known volume containing dry soil aggregates and weighing the sample.

Knowing the bulk density the total porosity, v_t, was computed as follows:

$$v_t = 1 - \frac{D_b}{D_f}$$

where D_b = bulk density and D_f = fabric density

Total porosities of soil aggregates, v_t, both from calculation and measurement, are as high as 0.60 (table 8). Aggregate porosities, v_{va}, were the average values measured from glassbead displacement and thin section methods, whereas v_{vs} were calculated by multiplying specific pore volume with bulk density of soil aggregates.

Data presented in table 8 show that aggregate porosity, v_{vs}, was about 0.18 for cultivated soils and 0.19 to 0.26 for virgin soils. The ratio of aggregate porosity, v_{vs}, to total porosity, v_t, was about 0.30 for cultivated soils and 0.30 to 0.40 for virgin soils. Sokolovskaya (35) showed data from which I calculated that pores with what the translation called "opening diameters" $<$5 microns, contributed to 0.35 of the total pore space for aggregates 5 to 0.25 mm diameter. The soils he used were cultivated soils.

Edwards et al. (18) found a minimum intra-ped porosity of 0.33 was required for corn growth. They also stated that intra-ped pore volume contributed more than 0.80 of the total pore volume. The discrepancy between Edwards et al. and these experiments arises from an erroneous concept of intra-ped porosity held by Edwards et al. They made no distinction between intra-ped porosity based on ped volume or on bulk soil volume. They therefore misused bulk density of a blocky soil as bulk density for discrete aggregates. The magnitude of these two quantities can not be equivalent. Edwards et al. obtained bulk densities of 1.39 to 1.43 g/cc for the surface soil, applying them for the discrete aggregates. Bulk densities of discrete aggregates in this experiment ranged from 0.80 to 1.05 g/cc, which are much smaller than the bulk densities of the surface mineral soils in field condition. Since Edwards et al. had mixed bases for calculating the 0.33 intra-ped porosity and 0.80 of the total pore volume contributing to intra-ped pore volume, these values are meaningless.

Table 8. Aggregate and Total Porosities for Soil Aggregates with Size of 3-5 mm Diameter.

Soil Type	Cond.	Total porosity		Aggregate porosity		v_{vs}/v_s
		Measured	Calc.	v_{va}	v_{vs}	
Aastad	V	.662	.624	.363	.211	.319
	C	.634	.613	.327	.191	.301
Bearden	V	.645	.597	.327	.191	.296
	C	.624	.579	.322	.187	.300
Clarion	V	.643	.602	.327	.191	.297
	C	.643	.607	.320	.187	.291
Fayette	V	.690	.678	.453	.264	.383
	C	.592	.583	.314	.182	.307
Hayden	V	.654	.638	.365	.212	.324
	C	.591	.595	.297	.172	.291
Tama	V	.670	.649	.410	.239	.357
	C	.660	.612	.324	.187	.283

Condition, virgin soil vs cultivated soil

Calculated values from Chepil's estimation (10)

Aggregate porosities are average values from glassbead displacement and thin section methods.

v_t is the measured total porosity.

SUMMARY AND CONCLUSIONS

Differences in aggregate porosity due to soil type, aggregate size and cultivation condition were investigated in this thesis.

Measurements were made on samples from six Minnesota soils. From each soil type a virgin and a cultivated sample were collected. Porosity characteristics were determined on naturally occurring aggregates and on artificial aggregates prepared from a pulverized sub-sample of each of the twelve. Four size fractions of aggregates were separated from each sample by sieving, namely 0.5-1, 1-3, 3-5, and 5-8 mm diameter.

Two alternative methods, glassbead displacement and thin section, were used to measure intraaggregate porosity, called aggregate porosity in this thesis. Hg-porosimeter measurements were used to find out the cumulative specific pore volume and the percentage of pore volume.

Aggregate porosity was higher in soils developed on loess and lower in those on till. Porosities ranged from 0.253 to 0.497 based on the aggregate volume.

Aggregate porosity of virgin soil was higher than that of cultivated soil at the 1 percent level. Aggregate porosity increased as aggregate size increased. It was also highly significant at 1 percent level.

The difference of aggregate porosity between artificial aggregates made from pulverized soil and natural aggregates was inconclusive. Naturally occurring aggregates had higher porosities at the 1 percent level for the data obtained from glassbead displacement method but the difference was not significant for the thin section method.

Nevertheless in the overall data there was general agreement between the glassbead displacement method and the thin section method as indicated by a matched-pairs t-test.

Specific pore volume of pores of diameters 0.012 to 17μ ranged from 0.124 to 0.272 cc/g as determined by Hg-porosimetry. Over 90 percent of the specific pore volume was contributed by pores of diameter greater than 0.2μ. The proportion of intraaggregate porosity to the total porosity was found to be about 0.30 for cultivated soils and 0.30 to 0.40 for virgin soils.

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