A CRITICAL STUDY OF THE METHODS FOR THE DETERMINATION OF WATER-STABLE AGGREGATES IN SOILS

by

S. D. NIJHAWAN

B. Sc.	(Hons), Punjab	University	Lahore	India,	1923
M. Sc.	"	"	"	"	, 1925
Ph.D.	"	"	"	"	, 1945

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INTRODUCTION

Soil structure is the distribution and arrangement of soil particles and determines the air-water relationships of soils. These particles may be of primary nature (sand, silt or clay) or secondary particles or aggregates which are formed by the union of primary particles held together by cementing agents. These cementing agents may be clay particles, organic matter, irreversible or slowly reversible inorganic colloids of iron and aluminum, or precipitated calcium carbonate.

Soil aggregates are responsible for two properties of fundamental importance to plant growth. Firstly, they are much less mobile than the primary particles from which they are formed, and they thus offer greater resistance to wind and water movement. Secondly, there are present a large amount of small pores inside the individual aggregates which are usually much finer than those between the aggregates. These fine pores inside the aggregates act as reservoirs for water and are surrounded by larger channels between the aggregates that allow for the draining of surplus water and for facilitating gaseous exchange between the soil air and the atmosphere.

Several attempts have been made to estimate the amount of aggregates in soils and many methods have been suggested. The methods that have been used do not seem to give a reliable estimate of the amount of aggregates existing in the field under varying conditions of climate, vegetation, and cultural and irrigation practices. Recently, however, the United States

Department of Agriculture has proposed a tentative method for the determination of "water-stable aggregates", meaning the aggregates which will not break or be deformed by the action of rains or irrigation practices. Experience has shown that the pretreatment of the soil sample greatly affects the size distribution of aggregates estimated by this method. This investigation was undertaken with the object of finding the factors responsible for such variations in analytical results.

REVIEW OF LITERATURE

Methods for the estimation of aggregates can broadly be divided into three groups: dry sieving to determine the actual size distribution of aggregates in the field, wet sieving to determine the distribution of water stable aggregates, and elutriation and sedimentation to determine the small aggregates and finer mechanical separates.

Dry Sieving

Dry sieving of soils is conducted on field dry soils. This method was used by Puchner (50) and Mangelsdorff (27) in Germany, by Keen (21) in England, Nekrassov (37) in Russia, Cole (13) in California, and Nijhawan (38) in India. Cole believes that sieving of air dry soil gives more reliable results than that of wet soil, because the aggregates in wet condition are so weakly held together that mechanical action of sieving is sufficient to break them. Tiulin (55), however, observed that sieving of a wet sample in xylene or benzene gave the same result as sieving of a dry sample.

Wet Sieving

Earliest attempts to determine water stable aggregates were made by Pigulevsky (48), Pavlov (43), and Tiulin (55), who sieved the soil under water instead of in air. Tiulin first wetted the sample by capillarity for 30 minutes after which he transferred it to a bank of sieves immersed in a tank of water. The sieves were taken in and out of water 30 times, allowing the water to drain away from the sieves between each immersion. The weight of soil left on each sieve was then determined.

The technique of Tiulin has been modified mainly in two directions; in the method of sieving and in the method of wetting the soil. Savinov (54) proposed that the bank of sieves should be plunged and then taken out completely with a jerk. Tsyganov (57) advised taking the sieves out one by one after they were finished, while Bouyoucos (7) used one sieve at a time.

Pigulevsky (48, 49) and Yoder (64) used mechanical means for moving the sieves up and down in the water.

Meyer and Rennenkampff (32) used fixed sieves but caused the water to rise up through the sieves to the top of the bank and then syphon away rapidly.

Elutriation and Sedimentation Methods

Wet sieving is the easiest method for determining water stable aggregates larger than 0.25 mm. in diameter but is not satisfactory for smaller aggregates. Elutriation and sedimentation methods have been used for determining particles having a diameter of less than one mm. An elutriator was used successfully for separating aggregates with diameters between 1 mm. and 0.02 mm. by Baver and Rhoades (4) and by Demolon and Hénin (15).

Cole and Edlefsen (14) criticised wet sieving and elutriation on the basis that mechanical action in water dispersed many aggregates. They designed a large sedimentation tube and determined the size distribution of particles by allowing them to fall through still water. This method was later used by Metzger and Hide (30) and Hide and Metzger (19) in their work to study the effect of certain crops and soil treatments on soil aggregates.

Bouyoucos (6), Peele (44, 45), and Gerdel (18) used a hydrometer instead of an elutriator to determine the amounts of the smaller soil aggregates. The distribution of particles smaller than 0.02 mm. was determined by the pipette method (42). Several workers such as Novak (40), Vilensky (58), Russell (51), Bertramson and Rhoades (5), Peele (46), Peele and Beale (47), and Van Doren and Stauffer (59) used sieves for fractions larger than 2 mm. to 0.25 mm. and used an elutriator, hydrometer, or pipette for the finer fractions.

McCalla (28) used a different technique for finding the stability of aggregates. Drops of water approximately 4 mm. in diameter falling one-half meter from a burette at a constant rate were allowed to strike moist particles of soil 4 mm. in diameter resting on a 1 mm. sieve and amount of energy required to break down an aggregate was worked out.

Browning, Russell and McHenry (12) compared Yoder's wet sieve method (64), a single sieve method, dispersion ratio as determined by Middelton (31), McCalla's water drop method (28), coefficient of aggregation as described by Retzer and Russell (52), and Bouyoucos' (6) hydrometer procedure. The authors found a general relationship between all the methods, but the single sieve and hydrometer methods gave higher results than Yoder's technique which shows that the former techniques were more gentle than Yoder's method. However, the advantage in Yoder's method is that the size distribution of aggregates is determined, a factor of great importance in establishing the physical characteristics of a soil.

Lutz (25), who compared elutriation and Yoder's sieve method, found that there was no difference in the amount of particles 0.1 mm. to 0.05 mm. found by the two methods.

The wet sieving technique has been used with success by most workers. According to Baver (3), wet sieving can be used with accuracy for separating aggregates larger than 0.25 mm. It has been found by Russian workers (24) that aggregates having diameters ranging from 0.25 mm. to 3 mm. constitute the stable structure of the soil and when aggregates in this size range are present the distribution of air and water in the soil is at an optimum. Elson (17), however, put 1 mm. as the lower limit because the soil morphologist separates the micro from the macro-aggregates at a diameter of 1 mm., and because it was found that, on the basis of the amount of alkali-soluble organic matter in the fractions, they could be divided into two size groups, those larger than 1 mm. and those smaller than this. Nijhawan (39) found that aggregates between 3 mm. and 0.25 mm. in diameter contained more clay, silt, exchangeable calcium, total nitrogen, and organic matter and were more water-stable than those larger than 3 mm. or smaller than 0.25 mm.

Pretreatment of Samples

The greatest problem in determining the distribution of soil aggregates is the manner in which the sample is prepared for analysis. Tiulin (55) wetted field moist soils by capillarity while workers like Baver and Rhoades (4) and Elson (16, 17) used samples at field moisture content. Other workers like Lutz (25), Peele (44, 45, 46), Browning et al. (9, 10, 11, 12), Woodruff (63), Johnston (20), Myers (33, 34), Myers and McCalla (36), and Ackerman and Myers (1) used air dry samples. These authors used air dry samples in order to have all the soils on a comparable basis, because, according to Yoder, the slaking process due to drying is complete only when the samples are allowed to approach closely an air dry condition. The dry soils are then wetted to cause complete disintegration of lumps. However, workers do not agree in regard to the best method of wetting the samples. Tsyganov (57) wetted the samples by capillarity, Pavlov (43), Bouyoucos (7) and Yoder (64) by immersing them in water, Vilensky (58) by capillarity followed by complete immersion, Wilson and Fisher (61) by two-hour immersion, and Peele (46) by three-hour immersion.

It was observed by Tsyganov (57), Yoder (64), and Russell (51) that air drying decreased the percentage of large aggregates in favor of the smaller. According to Woodburn (62), slaking was not complete if the air dry samples contained lumps between one-half and one-fourth inch and oven drying or shaking these in an end to end shaker was required to effect complete slaking.

However, Alderfer (2) has pointed out that soil moisture content is closely related to the amount and size of water stable aggregates. These findings are further corroborated by the work of Ackerman and Myers (1), Myers and McCalla (36), and Wilson and Browning (60), who found that wetting the soil increased the aggregation.

The method of wetting also brings about changes. According to Russell (51) the more rapidly the soil is wetted, the greater is the breaking of the larger aggregates. Thus, immersion of soil in water caused more destruction of the larger aggregates than wetting by capillarity and spraying water into the aggregates with an atomizer produced the least destruction. Russell (51) explained that this breaking of aggregates by wetting was due to the shattering effect of entrapped air in the capillaries which could not escape when the soil was rapidly wetted. According to Russell (51) when the soil is wetted under a vacuum, there is least degradation of soil aggregates and vacuum wetting can give a good measure of the inherent water-stability of the aggregates. Baver (3) takes exception to this view and points out that, "it does not obviate the disintegration effects of swelling that occur when a dried clod or aggregate is wetted".

Pigulevsky (49) in view of these results suggested that the analysis of air dry soil should be carried out by wetting the soil by an atomizer and then by immersing it in water.

Review of the literature brings out that it is essential to determine the size distribution of aggregates larger than 0.25 mm. and that these aggregates can be satisfactorily determined by the wet-sieving technique. However, there is a great difference of opinion regarding the methods of pretreating the sample and no uniform procedure is being followed. According to Baver the soils should not be completely dry if a true picture of the structure capacity is desired. Not much information is available on wetting by capillarity except the work of Tiulin (55) in Russia and no quantitative data are available on evacuation of air from the soil and then wetting it under vacuum.

EXPERIMENTAL METHODS

Methods of Analysis

The aggregate analyses were made by the method tentatively adopted by the Soil Conservation Service and the Bureau of Plant Industry of the United States Department of Agriculture (53) in 1943. In the main essentials this method is the same as Yoder's method (64), but in details it differs. Five-inch screens with openings 2, 1, 0.5, and 0.2 mm. wide, respectively, are used. Eighty-five grams of air dry soil, which has been passed through a one-half inch mesh screen, are placed on the 2 mm. screen and gently sifted to secure a uniform spread on the sieves. The fine soil passing through the 0.2 mm. sieve is placed in a six by nine inch battery jar containing water. The sieves are attached to the lift mechanism, and the glass jar containing three liters of distilled water is placed beneath them. The sieves are then lowered in the water in the vessel and the sample is sieved in water for 30 minutes at 35 cycles per minute with a vertical sieve displacement of three-fourth inch. The sieves are fixed to the lift mechanism in such a way that when it is raised up water just touches the bottom of the upper most screen. After the end of operation each sieve with soil on it is placed on a five and one-half inch watch glass and dried. The soil on each sieve after drying is transferred to a weighing bottle and dried at 105° C. to constant weight. The amount of particles below 0.02 mm. is determined by pipetting at 12 cm. depth, the suspension in the cylindrical vessel at an interval calculated according to Stokes' Law.

The amount of particles between 0.2 mm. to 0.02 mm. was determined by difference.

By this method it was possible to study size distribution of particles from 2 mm. to 0.02 mm. and the aggregation was expressed as the percentage, oven dry basis, of all material remaining on the sieves. As the samples contained a very small amount of sand grains larger than 0.2 mm., no correction was made for it.

Moisture equivalents of all the samples were determined by the centrifuge method (8). Determinations were made in quadruplicate or duplicate.

Soil Samples

Soils of varying texture and structure were collected from different parts of the State of Kansas. Samples of surface soil were obtained of Summit silt loam from Cowley county, Summit silty clay loam from Greenwood county, Parsons silt loam from Bourbon and Allen counties, Woodson silt loam from Allen county, Cherokee silt loam from Labette county, and Labette silt loam from Wilson county. For detailed work samples of surface and subsoil were obtained from the Agronomy Farm of the Kansas State Agricultural Experiment Station and from the Fort Hays, Kansas Branch Agricultural Experiment Station.

Samples of Geary silt loam were obtained at depths of 0-7 inches and 8-14 inches from a plot at the Agronomy Farm. This plot has been under row crops, oats, wheat, and alfalfa rotation and the aggregate analysis of the soil has already been reported by

Myers et al. (35). Samples from Hays were collected in sections of 0-5 inches and 6-10 inches from a winter wheat border plot. These were taken by means of a spade in four places in the plot and brought to the laboratory in air tight containers. In the laboratory the samples were passed through a one-half-inch mesh screen and thoroughly but gently mixed. A representative portion of the sample was dried in air while the remaining portion was stored in a moist condition in an air tight container. Before storing the moist sample, it was allowed to dry a little so that the soil particles should not ball together when stored.

Besides the above samples, soil cores taken at three-inch, nine-inch, and eighteen-inch depths from a continuous wheat plot at Fort Hays were obtained. These are numbered as Hays 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, and 77 and will be referred to in the text by these numbers.

Hays soils have not been identified into series, but they resemble the Crete series in description. They are hard pan soils, silty clay in texture with a clay content of about 43 per cent in the surface foot and 46 per cent in the second foot.

The moisture equivalents of the soils used in the experiments are given in Table 1. The moisture equivalent is an easily determined single measure that gives an estimate of the texture, structure and field water holding capacity of a soil. The results are expressed as moisture percentage on an oven dry basis.

Table 1. Moisture equivalents of soils.

Soil type	Plot	Moisture equivalent
		Per cent
Hays 65 3 inches	Continuous wheat	27.6
do 66 9 do	do do	33.0
do 67 18 do	do do	34.6
do 68 3 do	do do	27.7
do 69 9 do	do do	31.1
do 70 18 do	do do	33.8
do 71 3 do	do do	28.2
do 72 9 do	do do	29.3
do 73 18 do	do do	34.3
do 74 3 do	do do	28.6
do 75 9 do	do do	35.2
do 77 3 do	do do	29.1
do 0 - 5 do	Wheat border	28.4
do 6 -10 do	do do	31.4
do 0 - 3 do	Kafir border	27.5
Geary silt loam 0-7 inches	Corn, oats, wheat, alfalfa	26.5
do do do 8-14 do	do do do do	31.4
Summit silt loam surface soil	Corn fertility plots	21.7
Parsons silt loam do do (Bourbon county)	do do do	25.7
Woodson silt loam do do	do do do	24.3
Summit silty clay loam do do	do do do	23.9
Parsons silt loam do do (Allen county)	do do do	23.9
Cherokee silt loam do do	do do do	16.9
Labette silt loam do do	do do do	24.8

The soils had a very wide range of moisture equivalent values from 16.9 per cent in Cherokee silt loam to 35.2 per cent in Hays 75 at 9 inches. Therefore, the soils selected for the study had a sufficiently wide variation in texture and field water relationship to be quite representative of the soils of the state.

Wetting of Soil Samples

Air dry samples were wetted by means of: (a) capillarity, (b) an atomizer, (c) immersion, (d) pouring water on the soil, and (e) pouring water on the soil after air had been evacuated from it.

Soil samples were kept in contact with wet sand in order to wet them by capillarity. By adopting this technique it was possible to wet the samples slowly and uniformly and without puddling them. Sand that had been passed through a 2 mm. sieve was spread in a layer two inches thick in a small pan. The sand was saturated with distilled water, care being taken that no free water existed on the surface of the sand. The sample to be wetted was placed on the 2 mm. sieve. Two thick blotters were fixed under the bottom of the sieve for affecting a slow rise of water and preventing the fine particles of soil from passing through the sieve. The sample was kept on the sand until it was entirely wet. The blotters were removed and the sieve returned to the nest of sieves. The soil sticking to the blotter was removed by allowing the wet blotter to dry by placing it on a dry blotter for about a minute and was returned to the sieve. The bank of sieves was attached to the lifting mechanism and analyzed.

When soils were wetted with an atomizer, a weighed amount of the sample was placed in a cover glass and a fine spray was directed on them. The amount, rate, and intensity of spray from the atomizer could be controlled by adjusting the pressure of air used for working it. Soil on the cover glass was slowly turned by means of a spatula so that all the particles could be uniformly wetted. When the soil was thoroughly moistened, it was allowed to stand for an hour or so to allow the water to spread uniformly in the entire mass. Soil from the cover glass was transferred to the 2 mm. sieve in the nest and aggregate analysis was carried out on the sample.

For wetting the soil by immersion it was placed on the upper sieve and the entire nest of sieves was dipped into distilled water. Immediately after dipping the sieves they were removed from the water and allowed to stand for half an hour before running the sample for aggregate analysis.

Another method of wetting adopted was that of pouring water on the soil contained in a beaker.

Soil to be evacuated was placed in a beaker and put in a vacuum desiccator. The desiccator was attached to a Cenco-Hyvac vacuum pump, which could reduce the pressure in the desiccator to 0.01 mm. of mercury. The pressure in the desiccator was read on a manometer attached in the system or was evaluated by the intensity of electrical discharge in a vacuum tube attached to the desiccator. After the air had been removed, water was added to the soil in the desiccator through a capillary tube. A capillary tube was used so that water could be added slowly. If water was added rapidly there was danger of soil blowing out of the beaker when the water boiled under the reduced pressure. Four samples were evacuated at a time. Enough water was added to completely submerge the soil. Beakers were then removed from the desiccator and the soil transferred to the nest of sieves for carrying on the analysis.

EXPERIMENTAL RESULTS

Effect of Water Temperatures on the Amount and Size Distribution of Aggregates

In order to study the effect of the temperature of water at which the aggregate analysis is made, the analyses were carried out in water at 15° C. and at 47° C. The average results of four determinations are given in Table 2.

No differences were found in the total amounts or distribution of aggregates in the surface or subsoil samples of either soil at the two temperatures. Therefore, the water temperature at which the analysis is made is not important.

Table 2. Comparison of the amounts of water stable aggregates found in water at 47° C. with those found at 15° C.

Size of aggregate	Percentage of aggregates in soil on an oven dry basis			
	Hays 75, 0-9 inches		Hays 77, 0-3 inches	
	Water at 47° C.	Water at 15° C.	Water at 47° C.	Water at 15° C.
> 2 mm.	0.2	0.2	0.1	0.1
2 mm. to 1 mm.	1.1	1.5	1.1	1.2
1 mm. to 0.5 mm.	4.6	5.3	1.4	1.4
0.5 mm. to 0.2 mm.	13.7	13.6	5.7	4.5
0.2 mm. to 0.02 mm.	70.1	70.6	80.4	83.8
<0.02 mm.	10.4	8.8	11.3	9.0
Total aggregate >0.2 mm.	19.5	20.6	8.3	7.2

Effect of Drying Soils on the Amount and Size Distribution of Aggregates

Soil samples of Geary silt loam in two depths, 0-7 inches and 8-14 inches and Hays silty clay loam, 0-5 inches and 6-10 inches were brought to the laboratory in a field moist condition and immediately analyzed for water stable aggregates. They were then allowed to dry in air and aggregate analyses were carried out from time to time as their moisture content decreased. The average results for four replicates are given in Table 3, and the total amount of aggregates larger than 0.2 mm. is graphically represented in Fig. 1.

With a decrease in the moisture content of the soils there was a decrease in the amount of total aggregates larger than 0.2 mm. in all the four soils. The difference was more marked in the silty clay loam from Hays than in the Geary silt loam. Each had the highest amount of water stable aggregates larger than 0.2 mm. at a moisture content of about 20 per cent. With a decrease in moisture the total amount of aggregates larger than 0.5 mm. and those less than 0.02 mm. decreased while those between 0.5 mm. and 0.02 mm. increased. The extent of the decrease and increase varied with the nature of the soil. There was less decrease in sub-soil samples than in surface samples. At air dry moisture there was a decrease of from 55 to 80 per cent in the quantity of aggregates larger than 0.2 mm. in the case of the surface soil while the corresponding decrease in the sub-soil was only 17 to 35 per cent.

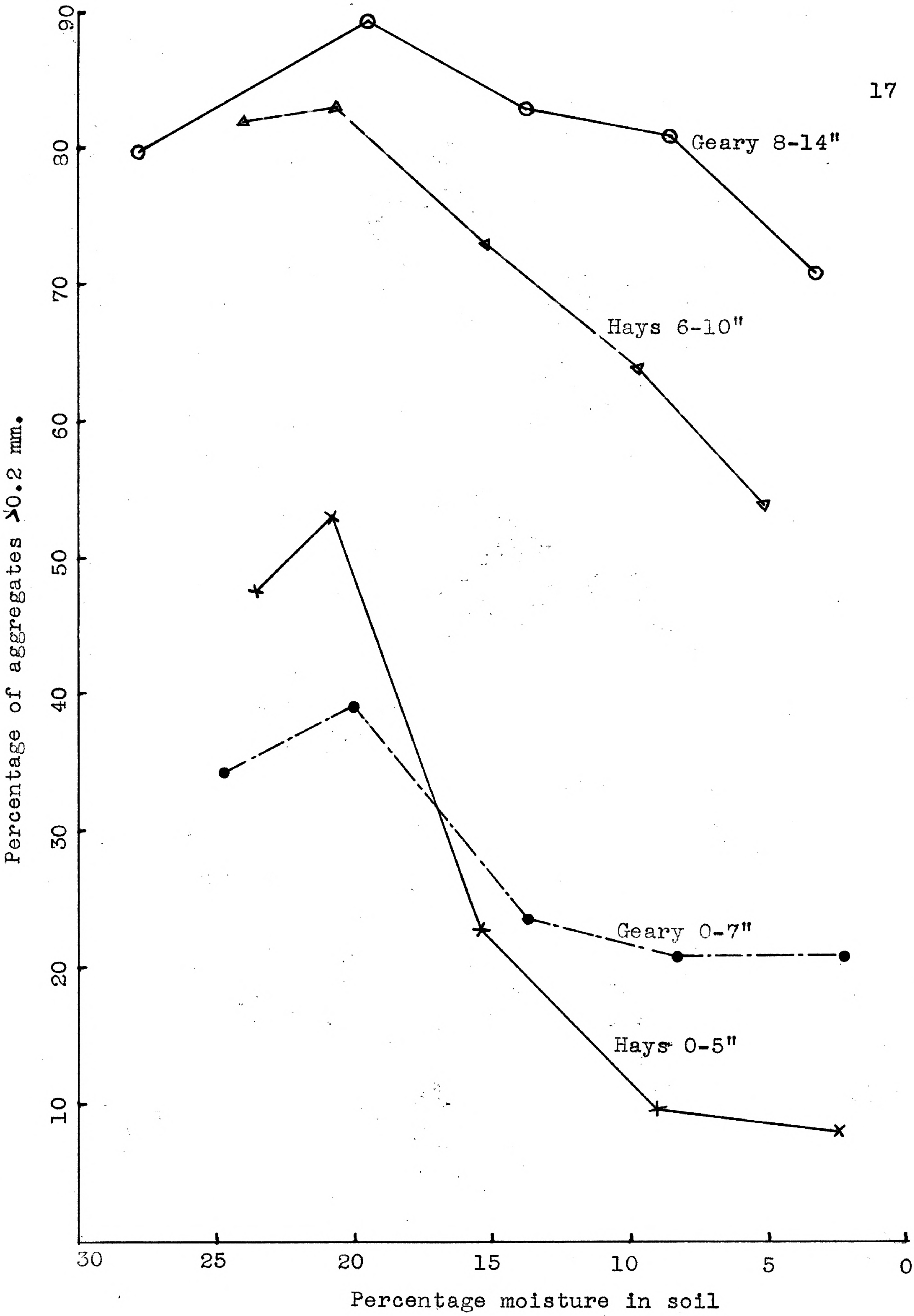

Fig. 1. Relation between moisture content of soils and the amounts of aggregates larger than 0.2 mm.

Table 3. Effect of drying field moist samples on the size distribution of soil aggregates.

Size of aggregates	Percentage of aggregates on an oven dry basis at indicated soil moisture content: Geary silt loam 0-7 inches					Geary silt loam 8-14 inches				
	24.79 per cent moisture	20.03 per cent moisture	13.71 per cent moisture	8.35 per cent moisture	*2.46 per cent moisture	27.98 per cent moisture	19.20 per cent moisture	11.66 per cent moisture	8.54 per cent moisture	*3.48 per cent moisture
> 2 mm.	8.2	14.1	9.6	3.5	1.3	29.3	30.8	21.4	15.6	5.2
2 mm. to 1 mm.	9.2	9.8	5.1	5.3	4.7	29.3	35.7	33.1	30.4	26.2
1 mm. to 0.5 mm.	10.0	9.2	4.8	5.8	6.4	14.1	17.0	19.8	22.3	23.0
0.5 mm. to 0.2 mm.	7.0	6.5	5.1	7.0	9.2	6.4	5.6	9.4	13.2	17.1
0.2 mm. to 0.02 mm.	36.9	36.5	53.6	66.3	70.9	7.2	5.6	12.1	14.8	24.4
< 0.02 mm.	28.7	23.9	21.8	12.1	7.5	13.7	5.3	4.2	3.7	4.1
Total aggregates > 0.2 mm.	34.4	39.6	24.6	21.6	21.6	79.1	89.1	83.7	81.5	71.5

Table 3 (cont.).

	Silty clay loam from Hays 0-5 inches					Silty clay loam from Hays 6-10 inches				
	23.26 per cent moisture	20.59 per cent moisture	15.13 per cent moisture	9.01 per cent moisture	*3.18 per cent moisture	24.10 per cent moisture	20.65 per cent moisture	15.22 per cent moisture	9.75 per cent moisture	*5.17 per cent moisture
>2 mm.	9.1	9.0	1.3	0.4	0.1	16.8	16.0	8.8	5.9	3.5
2 mm. to 1 mm.	13.6	13.2	3.4	1.3	0.8	32.4	29.2	24.4	18.7	14.7
1 mm. to 0.5 mm.	14.2	17.5	7.2	2.7	2.3	22.5	24.9	25.1	22.6	18.8
0.5 mm. to 0.2 mm.	10.6	14.2	10.5	5.1	5.5	11.2	12.9	15.5	17.6	17.4
0.2 mm. to 0.02 mm.	33.2	34.1	58.6	71.4	78.5	9.0	11.4	19.2	29.4	40.3
<0.02 mm.	19.3	12.0	19.0	19.1	12.8	8.1	5.6	7.0	5.8	5.3
Total aggregates >0.2 mm.	47.5	53.9	22.4	9.5	8.7	82.9	83.0	73.8	64.8	54.4

* Air dry moisture.

In surface samples the decrease in aggregation was the greatest between 20 per cent and 10 per cent moisture contents, while in the case of subsoil samples the decrease was greatest below 10 per cent moisture level.

Aggregate analysis of air dry sample has been used in the United States Department of Agriculture method and most investigators have carried out the analysis on air dry samples. The reason for doing so is that it is convenient to handle the samples in an air dry condition and that such a procedure places all samples on a comparable moisture basis. The other and the most important reason which has led to the adoption of this technique is that, according to Yoder (64), when air dry soils are immersed in water the aggregates are reduced to their ultimate sizes. To find out if further drying changed the size distribution of aggregates in any way the wet and air dried samples were dried at 105° C. for 24 hours, a time which experience showed was enough to completely dry the samples. The results which are the averages of four individual determinations are given in Table 4.

Oven drying further decreased the amount of aggregates larger than 0.2 mm. and increased those below 0.2 mm., especially in the case of the subsoil samples. The change in the surface soil samples was inconsistent and small and can be attributed to experimental error. The decrease in the subsoil samples amounted to from 34 to 26 per cent of the aggregates in the same soil when in an air dry condition, a very significant decrease.

Table 4. Comparison of the water stable aggregates found in air dry and oven dry samples.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis													
	Silty clay loam from Hays, surface soil		Silty clay loam from Hays, 0-5 inches			Silty clay loam from Hays, 6-10 inches			Geary silt loam 0-7 inches			Geary silt loam 8-14 inches		
	Air dry	Oven dry	Air dry	Moist to oven dry	Air to oven dry	Air dry	Moist to oven dry	Air to oven dry	Air dry	Moist to oven dry	Air to oven dry	Air dry	Moist to oven dry	Air to oven dry
>2 mm.	0.4	0.2	0.1	0.1	0.2	3.5	3.1	2.9	1.3	0.9	0.9	13.8	3.8	3.8
2 mm. to 1 mm.	1.7	1.5	0.8	0.7	1.0	14.7	6.8	8.0	4.7	2.8	3.0	33.0	18.7	15.9
1 mm. to 0.5 mm.	3.5	3.8	2.3	2.9	2.8	18.8	11.7	12.8	6.4	4.1	5.5	23.0	19.3	19.1
0.5 mm. to 0.2 mm.	8.8	10.7	5.5	8.8	7.7	17.4	15.2	16.0	9.2	6.9	8.0	13.2	15.0	15.4
0.2 mm. to 0.02 mm.	74.9	74.4	78.5	77.3	78.0	40.3	54.4	53.1	70.9	75.3	73.4	14.7	38.1	40.4
<0.02 mm.	10.7	9.4	12.8	10.2	10.3	5.3	8.8	7.2	7.5	10.0	9.2	2.3	5.1	5.4
Total aggregates >0.2 mm.	14.4	16.2	8.7	12.5	11.7	54.4	36.8	39.7	21.6	14.7	17.4	83.0	56.8	54.2

Amount and Size Distribution of Aggregates as Affected by Wetting of Samples

Because the treatment of the samples before the analysis has a very pronounced effect on the size distribution of aggregates, a detailed study was undertaken to find out the effect of the following pretreatments on the results of analysis: (a) immersion of soil in water, (b) addition of water to the soil, (c) wetting by capillarity, (d) wetting under vacuum, and (e) wetting by an atomizer.

Immersion of soils in water. Two surface and two subsoil samples from Hays were used to test the effect of immersion of air dry samples in water on the amount of water stable aggregates. The results are given in Table 5. Immersion in water decreased the amount of aggregates larger than 0.2 mm. and increased the fraction less than 0.02 mm. in both the surface soil samples. The effect was not very marked in the case of the subsoil samples, although both the soils showed a slight increase in the aggregates larger than 0.2 mm. These results suggest that the effect of immersion of soils in water will differ with the type of the soil, and will result in shattering of the aggregates in the comparatively lighter soils.

Pouring water on the soil. A second technique used was that of pouring water on air dry soil in a beaker. It differed from the first method of wetting as by this method chances for the escape of air from the capillaries were less, and, therefore, more shattering of aggregates by the entrapped air was expected. Surface and subsoil samples of Geary silt loam and Hays silty clay loam were used and the average results are reported in Table 6.

Table 5. Size distribution of aggregates as influenced by immersion in water before running the analysis.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis							
	Hays 69, silty clay loam, 9 inches		Hays 70, silty clay loam, 18 inches		Hays 71, silty clay loam, 3 inches		Hays 74, silty clay loam, 3 inches	
	No pre-treatment	Soil immersed in water	No pre-treatment	Soil immersed in water	No pre-treatment	Soil immersed in water	No pre-treatment	Soil immersed in water
>2 mm.	1.0	0.1	1.3	0.1	0.1	0.1	0.3	0.1
2 mm. to 1 mm.	3.6	3.7	4.0	4.1	1.0	0.3	0.7	0.4
1 mm. to 0.5 mm.	9.4	12.8	8.2	11.4	1.6	0.9	1.4	0.9
0.5 mm. to 0.2 mm.	18.5	17.7	15.0	14.7	5.6	3.8	6.8	3.1
0.2 mm. to 0.02 mm.	59.9	59.1	61.4	58.2	81.1	80.2	80.1	81.1
<0.02 mm.	7.6	6.6	10.1	11.5	10.6	14.7	10.7	14.4
Total aggregates >0.2 mm.	32.5	34.3	28.5	30.3	8.3	5.1	9.2	4.5

Table 6. Effect of wetting soil samples by pouring water on them on the amount and size distribution of aggregates.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis							
	Geary silt loam, 0-7 inches		Geary silt loam, 8-14 inches		Hays silty clay loam, 0-5 inches		Hays silty clay loam, 6-10 inches	
	No pre-treatment	Water poured on soil	No pre-treatment	Water poured on soil	No pre-treatment	Water poured on soil	No pre-treatment	Water poured on soil
>2 mm.	4.0	1.0	5.2	9.8	0.2	0.1	3.7	1.6
2 mm. to 1 mm.	5.9	3.8	26.2	28.1	1.5	0.5	13.7	13.5
1 mm. to 0.5 mm.	7.2	7.2	23.0	22.9	3.5	3.1	18.4	20.3
0.5 mm. to 0.2 mm.	10.5	11.6	17.1	14.7	7.8	9.7	17.9	18.5
0.2 mm. to 0.02 mm.	67.5	71.2	24.4	21.0	79.2	76.7	41.7	40.4
<0.02 mm.	4.9	8.3	4.1	3.5	7.8	9.9	4.7	5.7
Total aggregate >0.2 mm.	27.6	23.6	71.5	75.5	13.0	13.4	53.6	53.9

There was no effect of treatment on either of the samples of soil from Hays, although in the case of Geary silt loam there was a decrease in the aggregates greater than 0.2 mm. in the surface soil and a slight increase in the subsoil sample. There was no pronounced effect of the treatment although the results suggest that the effect will vary with the nature of the soil.

Comparison of wetting of soils by capillarity, after evacuation, by an atomizer, and by pouring water on the soil. Surface and subsoil samples of Geary silt loam and the silty clay loam from Hays were wetted by pouring water on soil, by capillarity, by wetting under a vacuum, by wetting with an atomizer, and by pouring water on the soil. The results are given in Table 7.

As compared to the above two methods of wetting, wetting by capillarity resulted in considerable increase in the amount of aggregates larger than 0.2 mm. Increases were greater in the surface soil samples than in the subsoil samples. In all the soils, there was a decrease in the soil aggregates less than 0.5 mm. and a corresponding increase in all the aggregates greater than 0.5 mm.

When soils were wetted after the air was evacuated from them, there was a great increase in the amount of aggregates larger than 0.2 mm. as compared to the air dry soil which was wetted by addition of water to the soil without evacuating the sample.

Table 7. Effect of different methods of wetting on the amount and size distribution of aggregates.

Size of aggregates	Percentage of aggregates on an oven dry basis							
	Water poured on soil	Wetting by capillarity	Wetting under vacuum	Wetting by atomizer	Water poured on soil	Wetting by capillarity	Wetting under vacuum	Wetting by atomizer
	Geary silt loam, 0-7 inches				Geary silt loam, 8-14 inches			
	3.4 Per cent moisture	36.1 Per cent moisture	-- Per cent moisture	21.7 Per cent moisture	4.8 Per cent moisture	35.0 Per cent moisture	-- Per cent moisture	28.2 Per cent moisture
>2 mm.	1.0	35.5	36.5	19.5	9.8	39.2	22.0	22.7
2 mm. to 1 mm.	3.8	22.9	21.8	27.8	28.1	35.6	33.8	41.4
1 mm. to 0.5 mm.	7.2	18.4	20.5	26.8	22.9	13.7	25.0	22.1
0.5 mm. to 0.2 mm.	11.6	6.9	8.0	11.8	14.7	3.6	7.0	8.2
0.2 mm. to 0.02 mm.	71.1	12.8	10.2	12.7	21.0	5.7	9.4	3.6
<0.02 mm.	8.3	3.5	3.0	1.4	3.5	2.2	2.8	2.0
Total aggregates >0.2 mm.	23.6	83.7	86.8	85.9	75.5	92.1	87.8	94.4

Table 7 (cont.).

	Hays silty clay loam, 0-5 inches				Hays silty clay loam, 6-10 inches			
	3.8	39.7	--	27.1	4.2	39.9	--	31.7
	Per cent moisture	Per cent moisture	Per cent moisture	Per cent moisture	Per cent moisture	Per cent moisture	Per cent moisture	Per cent moisture
>2 mm.	0.1	37.1	32.2	14.8	3.7	24.7	10.8	11.5
2 mm. to 1 mm.	0.5	18.4	13.9	24.6	13.6	35.8	26.9	34.5
1 mm. to 0.5 mm.	3.1	13.2	12.4	22.0	18.4	17.2	22.4	26.6
0.5 mm. to 0.2 mm.	9.7	9.6	10.5	7.7	17.9	7.9	15.3	13.3
0.2 mm. to 0.02 mm.	76.7	17.6	26.2	27.3	41.7	11.6	20.3	10.8
<0.02 mm.	9.9	4.1	4.8	3.6	4.7	2.8	4.3	3.3
Total aggregates >0.2 mm.	13.4	78.3	69.0	69.1	53.6	85.6	75.4	85.9

The percentage of aggregates larger than 0.2 mm. in the air dry samples of the four soils was 23.6, 75.5, 13.4, and 53.6 as compared to corresponding percentages of 86.8, 87.8, 69.0, and 75.4 in the soils wetted under vacuum. These results, however, were lower than those obtained by wetting the samples by capillarity except in the case of Geary silt loam surface sample which in both cases are of the same order. The differences were not great in the two subsoil samples but were considerable in the case of Hays surface soil. Figures for total aggregates obtained for this soil by wetting by capillarity and under vacuum are 78.3 and 69.0 per cent respectively.

When the soils were wetted with an atomizer, the percentages of aggregates obtained were of the same order as obtained by capillarity wetting, except in the case of silty clay loam from Hays, 0-5 inches which gave less aggregation when wetted by an atomizer than when wetted by capillarity. The reason for this discrepancy is not known.

Although there was a close agreement in the total amount of aggregates larger than 0.2 mm., there was a very marked difference in size distribution. Wetting by capillarity resulted in a considerable increase in the aggregates larger than 2 mm. size, amounting to nearly twice that formed by wetting with an atomizer. Wetting with an atomizer brought about an increase in the quantity of aggregates between 2 mm. and 1 mm. and it was more than was formed by any other pretreatment.

The work reported in the last pages was conducted on two types of soils with their moisture-equivalents varying from 26.5

to 31.4 per cent. Seven more soils with their moisture equivalent varying from 16.9 to 25.7 per cent were obtained, representing a very wide area of the state. Samples in an air dry condition were wetted by capillarity, under vacuum, and by an atomizer, after which aggregate analyses were carried out. The results are given in Table 8.

Wetting by capillarity by keeping the samples on wet sand gave the highest amount of aggregates larger than 0.2 mm. The lowest amounts of aggregates obtained in air dry samples were only one-third or one-fourth as great as those obtained when the soils were wetted on sand. When wetted under a vacuum, aggregates larger than 0.2 mm. were 5 to 8 per cent lower than those wetted by capillarity in the case of four samples, while these were equal in the remaining three. Wetting by an atomizer gave lower results than were obtained by wetting on sand or under a vacuum except in the case of Summit silty clay loam in which case they were higher. This is in accord with the results already reported in which case wetting heavy textured soils with an atomizer gave higher percentage of aggregates larger than 0.2 mm.

Wetting under a vacuum gave a maximum amount of aggregates larger than 2 mm. while air drying gave the least. Wetting by all methods decreased the amount of particles between 0.2 mm. to 0.02 mm. and in some cases those less than 0.02 mm.

Table 8. Effect of pretreatments (air drying, wetting by capillarity, under vacuum, and by an atomizer) on the size distribution of aggregates.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis							
	Air dry	Wetted on sand	Wetted under vacuum	Wetted by an atomizer	Air dry	Wetted on sand	Wetted under vacuum	Wetted by an atomizer
	Summit silt loam				Parsons silt loam			
	1.8 Per cent moisture	34.3 Per cent moisture	1.8 Per cent moisture	24.7 Per cent moisture	1.9 Per cent moisture	31.2 Per cent moisture	1.9 Per cent moisture	25.9 Per cent moisture
> 2 mm.	0.2	5.0	16.1	0.2	0.8	23.5	19.8	8.1
2 mm. to 1 mm.	0.6	8.9	3.4	3.0	4.4	25.7	25.9	16.4
1 mm. to 0.5 mm.	2.3	12.0	4.6	7.9	7.7	20.7	20.3	23.3
0.5 mm. to 0.2 mm.	5.8	10.8	7.3	11.8	12.1	12.6	9.9	15.4
0.2 mm. to 0.02 mm.	77.3	52.8	56.4	63.6	61.6	11.8	17.2	22.4
< 0.02 mm.	13.8	10.5	12.2	13.5	13.4	5.7	6.9	14.4
Total aggregate > 0.2 mm.	8.9	36.7	31.4	22.9	25.0	82.5	75.9	63.2
	Woodson silt loam				Summit silty clay loam			
	2.0 Per cent moisture	30.1 Per cent moisture	-- Per cent moisture	25.8 Per cent moisture	2.4 Per cent moisture	34.2 Per cent moisture	-- Per cent moisture	25.8 Per cent moisture
> 2 mm.	0.2	31.7	20.6	13.4	2.7	29.6	41.9	7.8
2 mm. to 1 mm.	1.6	20.2	15.9	14.9	3.7	15.3	8.3	19.7
1 mm. to 0.5 mm.	4.9	17.5	20.7	16.4	4.8	12.4	8.3	27.3
0.5 mm. to 0.2 mm.	9.2	11.3	15.5	5.8	7.5	9.1	7.8	17.9
0.2 mm. to 0.02 mm.	73.1	14.1	19.9	41.6	68.9	22.2	26.1	17.7
< 0.02 mm.	11.0	5.2	7.4	7.9	12.4	11.4	7.6	9.6
Total aggregate > 0.2 mm.	15.9	80.7	72.7	50.5	18.7	66.4	66.3	72.7

Table 8 (cont.).

Size of aggregates	Parsons silt loam: Air dry (1.8 Per cent moisture)	Parsons silt loam: Wetted on sand (31.5 Per cent moisture)	Parsons silt loam: Wetted under vacuum (-- Per cent moisture)	Parsons silt loam: Wetted by an atomizer (18.3 Per cent moisture)	Cherokee silt loam: Air dry (1.0 Per cent moisture)	Cherokee silt loam: Wetted on sand (31.2 Per cent moisture)	Cherokee silt loam: Wetted under vacuum (-- Per cent moisture)	Cherokee silt loam: Wetted by an atomizer (19.7 Per cent moisture)
	Percentage of aggregates in soil on an oven dry basis							
> 2 mm.	0.3	13.1	37.5	9.2	4.9	21.9	25.5	17.8
2 mm. to 1 mm.	1.5	25.9	14.8	15.6	5.1	17.4	10.8	15.0
1 mm. to 0.5 mm.	4.6	22.5	11.3	23.9	4.8	11.3	8.0	12.1
0.5 mm. to 0.2 mm.	8.6	10.3	7.9	17.0	5.9	6.6	6.1	7.0
0.2 mm. to 0.02 mm.	77.4	22.6	22.2	26.3	69.8	36.5	41.9	38.8
< 0.02 mm.	7.6	5.6	6.3	8.0	9.5	6.3	7.7	9.3
Total aggregates > 0.2 mm.	15.0	71.8	71.5	65.7	20.7	57.2	50.4	51.9

Size of aggregates	Labette silt loam: Air dry (2.1 Per cent moisture)	Labette silt loam: Wetted on sand (37.2 Per cent moisture)	Labette silt loam: Wetted under vacuum (-- Per cent moisture)	Labette silt loam: Wetted by an atomizer (20.0 Per cent moisture)
> 2 mm.	2.7	18.8	31.0	17.8
2 mm. to 1 mm.	7.7	27.5	22.2	29.4
1 mm. to 0.5 mm.	8.3	22.5	17.4	21.9
0.5 mm. to 0.2 mm.	11.9	12.4	10.6	4.0
0.2 mm. to 0.02 mm.	60.1	14.6	13.5	21.7
< 0.02 mm.	9.3	4.2	5.3	5.2
Total aggregates > 0.2 mm.	30.6	81.2	81.2	73.1

There was more moisture in the samples wetted on sand than those wetted by an atomizer. The moisture at the time of analysis in the samples wetted on sand varied from 30.1 to 37.2 per cent while in those wetted by an atomizer it was 18.3 to 25.9 per cent. These results show that the lower amount of moisture was not responsible for the low aggregation obtained by wetting with an atomizer. Summit silt loam was analyzed at two moisture contents, 24.7 and 20.4 per cent, its moisture-equivalent being 21.7 per cent. The results of analysis, which are given in Table 9, show that there was no difference in the amount of aggregates larger than 0.2 mm. or in the size distribution of aggregates.

Table 9. Results of aggregate analysis of Summit silt loam at two moisture levels.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis at indicated soil moisture content: 20.4 per cent moisture	24.7 per cent moisture
>2 mm.	0.2	0.2
2 mm. to 1 mm.	2.8	3.0
1 mm. to 0.5 mm.	8.8	7.9
0.5 mm. to 0.2 mm.	13.1	11.8
0.2 mm. to 0.02 mm.	62.5	63.6
<0.02 mm.	12.6	13.5
Total aggregates >0.2 mm.	24.9	22.9

These results suggest that the distribution of moisture and not the amount of moisture is the factor which determines the stability of an aggregate in water.

The above comparison of the methods of wetting suggests that wetting by capillarity gives the maximum amount of aggregates larger than 0.2 mm. and that wetting under a vacuum gives the next highest amount. Wetting under a vacuum gives more consistent results than the above two methods of wetting. The choice between wetting by capillarity and under a vacuum depends on what one is to determine. In the case of wetting by capillarity swelling of the soil is probably responsible for shattering the aggregates. A film of water around the particles may help to keep the particles together and may protect the aggregates from being broken when worked in water. The degree to which these two forces are effective will determine the size distribution of aggregates. The results show that in the majority of samples wetted by capillarity there is a larger amount of aggregates greater than 2 mm. in diameter, which suggests that the forces of adhesion are stronger than those of swelling. How these forces are effective in the other two methods of wetting is a problem to be worked out.

There is a difference of opinion in the literature about the effect of water in stabilizing soil aggregates. According to Russell (51) there will be an increase in the stable aggregates with an increase in moisture content as the water provides dipole linkage bonds and when these are provided further addition of water will have no effect. However, McHenry and Russell (29) found that clay and sand mixtures showed a decrease in water stability as the moisture at the time of sieving was increased.

Wetting of soils in the vapor phase. Cores of soils from Hays obtained at 3, 9, and 18 inch depths were placed in a humidor. After being stored in the humidor for nearly two months, they were taken out, passed through a one-half-inch mesh screen and analyzed. The remaining soil was again returned to the humidor and the humidor was kept over an oven whose inside temperature was 105° C. In this case wetting of soils by drops of water which had condensed on the top of the humidor could not be completely avoided, although every attempt was made to wipe these drops off as soon as they were formed. It can, however, be said that a large proportion of water was added in the vapor phase. These samples were also wetted by capillarity by keeping the samples on wet sand. The results of aggregate analysis of the soil wetted in a humidor to two levels of moisture, those wetted by capillarity and that of the air dry sample, are given in Table 10.

Soils 68, 65, 66 and 67 in an air dry condition had a moisture content of 1.9, 1.3, 1.5 and 1.3 per cent, respectively, and the corresponding moisture contents when kept in a humidor at room temperature were 6.6, 6.7, 9.4, and 10.3 per cent, respectively. By keeping the humidor at a higher temperature, moisture varied from 9.4 per cent to 17.4 per cent, surface samples having lower moisture contents than the subsoils.

The results of analysis show that the total aggregates larger than 0.2 mm. increased with an increase in the moisture content. Two subsoil samples at 16.3 per cent and 17.4 per cent had 95.2 per cent and 95.5 per cent of aggregates larger than 0.2 mm.

Table 10. Effect of placing the soils in a humidor on the size distribution of aggregates.

Size of aggregates	Percentage of aggregates on soil on an oven dry basis															
	Hays 68, silty clay loam, 3 inches				Hays 65, silty clay loam, 3 inches				Hays 66, silty clay loam 9 inches				Hays 67, silty clay loam 18 inches			
	Air dry	Kept in humidor		Wetted by capillarity	Air dry	Kept in humidor		Wetted by capillarity	Air dry	Kept in humidor		Wetted by capillarity	Air dry	Kept in humidor		Wetted by capillarity
	1.9 per cent moisture	6.6 per cent moisture	14.7 per cent moisture	34.9 per cent moisture	1.3 per cent moisture	6.7 per cent moisture	9.5 per cent moisture	34.0 per cent moisture	1.5 per cent moisture	9.4 per cent moisture	16.3 per cent moisture	31.0 per cent moisture	1.3 per cent moisture	10.3 per cent moisture	17.4 per cent moisture	38.7 per cent moisture
> 2 mm.	0.2	0.5	29.5	38.7	0.1	0.7	12.3	28.5	0.2	3.6	52.7	62.4	0.1	2.9	23.9	44.0
2 mm. to 1 mm.	1.6	2.1	18.8	17.5	0.8	1.7	19.4	17.5	6.3	13.1	24.6	17.0	5.8	8.6	35.6	30.3
1 mm. to 0.5 mm.	5.8	3.4	18.1	14.7	3.3	2.9	28.4	17.3	14.3	19.6	12.5	10.5	11.4	14.8	26.2	15.2
0.5 mm. to 0.2 mm.	8.0	10.0	7.9	10.1	7.1	10.6	5.7	15.0	18.3	20.5	6.4	5.9	18.0	23.0	9.8	6.7
0.2 mm. to 0.02 mm.	73.8	76.2	22.4	16.1	77.3	75.4	30.8	18.4	51.9	38.0	1.7	1.9	53.9	43.5	2.6	1.9
< 0.02 mm.	10.6	7.8	3.3	2.9	11.4	8.7	3.4	3.3	9.0	5.2	2.1	2.3	10.8	7.2	1.9	1.9
Total aggregates > 0.2 mm.	15.6	16.0	74.3	81.0	11.3	15.9	65.8	78.3	39.1	56.8	96.2	95.8	35.3	49.3	95.5	96.2

which figures are exactly the same as obtained in the samples wetted by capillarity. There was also a considerable increase in total aggregates of the surface soil samples but these were lower than obtained by capillary wetting.

These results bring forth a very important fact, and that is that the aggregation in the soil is not only controlled by the moisture content of the soil but that the distribution of moisture in the capillaries is of greater importance than the absolute moisture status of the soil.

Effect of wetting soils to a low moisture content by the addition of water. In order to find out how wetting of the sample to a moisture content below its field saturation capacity or moisture-equivalent affected the aggregation, two subsoil samples, Hays 72 and 73, obtained from the same field as the samples kept in humidor, were wetted by spraying water on them. The results of aggregate analysis are given in Table 11.

Table 11. Effect of wetting with a small stream of water on the amount and size distribution of aggregates.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis			
	Hays 72, 9 inches		Hays 73, 18 inches	
	Air dry 3.9 per cent moisture	Wetted 19.7 per cent moisture	Air dry 4.4 per cent moisture	Wetted 19.2 per cent moisture
> 2 mm.	0.2	0.3	0.1	0.3
2 mm. to 1 mm.	2.3	4.8	2.3	5.2
1 mm. to 0.5 mm.	7.2	11.9	8.4	13.8
0.5 mm. to 0.2 mm.	15.0	15.9	17.9	19.8
0.2 mm. to 0.02 mm.	66.1	54.0	61.8	48.9
< 0.02 mm.	9.2	13.1	9.5	12.0
Total aggregates >0.2 mm.	24.7	32.9	28.7	39.1

The above results clearly show that addition of moisture in the vapor phase was more effective than the water added in the liquid phase. The moisture content in these samples was raised from 3.9 per cent to about 19 per cent, which was higher than in the samples in the humidor, but they only contained 32.9 and 39.7 per cent of aggregates larger than 0.2 mm. as against 95 per cent in samples kept over a humidor.

Evacuation Studies

When soils were evacuated it was found that the amount of aggregates larger than 0.2 mm. in certain soils was less than those found by capillarity wetting; therefore, the samples were evacuated for different periods to find out if length of time was not responsible for low values. The samples were evacuated for 3, 6, 24 and 48 hours and the data are given in Table 12.

Table 12. Effect of evacuating the samples for different periods of time on the size distribution of water stable aggregates.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis after indicated period of evacuation															
	Geary silt loam, 0-7 inches				Geary silt loam, 8-14 inches				Silty clay loam from Hays 0-5 inches				Silty clay loam from Hays 6-10 inches			
	3 Hrs.	6 Hrs.	24 Hrs.	48 Hrs.	3 Hrs.	6 Hrs.	24 Hrs.	48 Hrs.	3 Hrs.	6 Hrs.	24 Hrs.	48 Hrs.	3 Hrs.	6 Hrs.	24 Hrs.	48 Hrs
> 2 mm.	23.6	33.8	36.5	26.6	23.2	22.0	30.4	29.1	32.2	30.0	30.8	28.1	11.1	11.6	10.8	10.7
2 mm. to 1 mm.	26.0	23.2	21.8	23.0	33.8	33.8	32.1	28.7	13.9	13.5	13.9	13.6	23.3	24.8	26.9	24.2
1 mm. to 0.5 mm.	25.2	18.9	20.5	23.6	21.0	25.0	16.4	21.6	12.4	12.7	13.7	12.1	24.4	23.6	22.4	23.3
0.5 mm. to 0.2 mm.	9.5	8.5	8.0	9.9	9.0	7.0	8.4	8.2	10.5	11.8	10.5	11.4	16.3	14.8	15.3	16.3
0.2 mm. to 0.02 mm.	12.2	12.3	10.2	13.9	10.0	9.4	9.7	9.4	26.2	27.0	26.4	28.5	20.4	20.8	20.3	21.0
< 0.02 mm.	3.5	3.3	3.0	3.0	3.0	2.8	3.0	3.0	4.8	5.0	4.7	6.3	4.5	4.4	4.3	4.5
Total aggregates > 0.2 mm.	84.3	84.4	86.8	83.1	87.0	87.8	87.3	87.6	69.0	68.0	68.9	65.2	75.1	74.8	75.4	74.5

The results for total aggregates were practically the same whether the soil was evacuated for three hours or 48 hours. During the investigation, however, it was observed that for complete removal of the air a high vacuum is required. Whether or not the vacuum pump used, which gave a vacuum of 1/100th of a millimeter, was able to remove all the air is a question which requires further investigation.

It was further suggested that heating of the samples prior to evacuation might help in removing the air completely. Therefore, soils were kept in an oven for a period of six hours and while still hot were removed to a vacuum dessicator and evacuated. The results of aggregate analysis carried out on these samples are given in Table 13.

Heating of the sample prior to evacuation slightly increased the amount of total aggregates in Hays silty clay loam surface soil and in the Summit soil but it decreased the aggregation in the case of Geary silt loam. With Summit silt loam, a comparatively light textured soil, a great difference in the size distribution of aggregates existed. The amount of aggregates larger than 2 mm. was nearly doubled in the heated sample.

These results suggest that the heating of the samples of light textured soils may hasten evacuation and result in an increase in the large sized aggregates.

Table 13. Effect of heating of the sample prior to wetting under vacuum on the size distribution of aggregates.

Size of aggregates	Percentage of aggregates in soil on an oven dry basis									
	Geary silt loam				Silty clay loam from Hays				Summit silt loam surface soil	
	0-7 inches		8-14 inches		0-5 inches		6-10 inches			
	Un-heated	Heated	Un-heated	Heated	Un-heated	Heated	Un-heated	Heated	Un-heated	Heated
> 2 mm.	28.8	28.2	22.6	19.3	31.0	30.3	11.3	4.8	7.7	16.1
2 mm. to 1 mm.	24.6	24.8	33.8	29.9	13.7	16.1	24.1	17.8	3.7	3.5
1 mm. to 0.5 mm.	22.0	20.6	23.0	21.4	12.6	14.7	24.0	23.4	8.6	4.6
0.5 mm. to 0.2 mm.	9.0	9.6	8.0	10.6	11.2	11.6	15.6	21.3	10.1	7.3
0.2 mm. to 0.02 mm.	12.2	13.4	9.7	15.1	26.6	23.6	20.6	27.8	57.1	56.4
< 0.02 mm.	3.4	3.4	2.9	3.7	4.9	3.7	4.4	4.9	12.9	12.1
Total aggregates >0.2 mm.	84.4	83.2	87.4	81.2	68.5	72.7	75.0	67.3	30.1	31.5

Distribution of Aggregates as Influenced by Storage of Moist Samples

Periodic analysis of samples stored in air tight containers indicated that there was an increase in the aggregates larger than 0.2 mm. and the analysis of the samples after a month and a half showed that the total aggregates had become as high as in the samples wetted by capillarity, although the moisture content had decreased slightly. The results of analysis after different periods of time are reported in Table 14.

In each case, the aggregation of the soil increased with the time of storage in a moist condition. The increase in aggregation may again be explained in the redistribution of moisture in the stored samples. The humidity of the air in the air tight containers increased and this might have deposited water in the fine capillaries and displaced the entrapped air.

There was a greater increase in the total aggregates of the surface soils than the subsoils. This increase, in addition to the desposition of moisture in fine capillaries, may have been also due to a uniform distribution of moisture on storage. In the field there is a moisture gradient, moisture increasing with the depth. The top soil has less moisture than the soil below. When the surface soil samples were mixed in the laboratory and stored, the moisture from the wet soil grains may have moved and increased the moisture content of the dry grains and displaced the air in them. This consequently resulted in the large increase of aggregates larger than 0.2 mm. size.

Table 14. Distribution of aggregates as influenced by storage of moist samples.

Size of aggregates	Percentage of aggregation in soil on an oven dry basis									
	Geary silt loam, 0-7 inches			Geary silt loam, 7-14 inches			Silty clay loam from Hays 0-5 inches		Silty clay loam from Hays 6-10 inches	
	Sampled 4-24-47 25.6 per cent moisture	Sampled 4-29-47 22.8 per cent moisture	Sampled 6-12-47 22.6 per cent moisture	Sampled 4-24-47 27.6 per cent moisture	Sampled 4-29-47 25.3 per cent moisture	Sampled 6-14-47 25.1 per cent moisture	Sampled 5-2-47 23.3 per cent moisture	Sampled 6-16-47 22.3 per cent moisture	Sampled 5-2-47 24.1 per cent moisture	Sampled 6-24-47 23.7 per cent moisture
> 2 mm.	14.2	9.8	31.7	33.5	33.7	45.5	9.1	21.5	16.8	24.0
2 mm. to 1 mm.	8.5	8.7	19.4	28.8	34.1	33.2	13.6	19.6	32.4	34.8
1 mm. to 0.5 mm.	9.5	8.6	16.0	12.8	16.1	12.2	14.2	20.3	22.5	22.1
0.5 mm. to 0.2 mm.	6.6	5.9	6.6	5.8	5.4	3.5	10.6	12.7	11.2	9.8
0.2 mm. to 0.02 mm.	33.0	36.2	14.1	7.9	3.0	1.9	33.2	17.0	9.1	4.1
< 0.02 mm.	28.2	30.8	12.2	11.2	7.7	3.7	19.3	8.9	8.0	5.2
Total aggregates >0.2 mm.	38.8	33.0	73.7	80.9	89.3	94.4	47.5	74.1	82.9	90.7

That the increase in aggregation was not due to balling of soil aggregates into larger lumps was ascertained by passing the stored sample through a one-half mesh screen. The entire soil passed through the screen, showing that the size of the soil lumps was not changed in storage.

DISCUSSION

Methods of aggregate analysis, the way of expressing data, and the procedure adopted in collecting and preparing samples for analysis vary widely with the investigators, although the variations are greater in the latter two procedures than in the methods of analysis. This probably is due to the failure of some investigators to recognize the importance of the factors that affect aggregation, to differences of opinion regarding the size fraction which determines the structural relationship of soils, and to the large difference in physical and chemical characteristics of the soils that are being studied.

In the use of methods for aggregate analysis there is sufficient uniformity in procedure. For determining the nature of tilth as affected by cultivation practices, dry sieving gives satisfactory results; for determining water stable aggregates, wet sieving is the usual procedure adopted.

Methods of expressing aggregate analysis data vary greatly because very few investigations have been undertaken to determine the size of aggregates that produce optimum conditions of air and moisture relationships in the soil and maximum crop yields. According to work of investigators like Doyarenko, as quoted by Krause (24), Yoder (65), and Nijhawan (39) for obtaining optimum yields of crops the soil should have stable crumbs between 5 mm. and 6 mm. in diameter. According to Tiulin (56) aggregates larger than 0.25 mm. are responsible for stable soil structure. The lowest size limit of soil aggregates that determines the structural stability or the yields of crops may be 0.25 mm. and to determine smaller fractions than this, as suggested by Kolodny and Joeffe (22) or Kolodny and Neal (23), may not be of much practical value.

The greatest limiting factor in the determination of water stable aggregates is the preparation of the sample for analysis. Almost all workers have used air dry samples for analysis and the tentative method recommended by United States Department of Agriculture recommends running the analysis on an air dry sample.

According to Yoder (64) the slaking of the sample was complete only when the lump of soil was allowed to approach closely an air dry condition. The results obtained during the present investigation clearly indicate that it is not true of every soil. Oven drying of moist and air dry samples of the Geary silt loam and silty clay loam (6-10 inches) from Fort Hays (Table 4) decreased the aggregates larger than 0.5 mm. by about 28 per cent and increased the fraction below 0.2 mm., although the aggregates between 0.5 to 0.2 mm. remained more or less constant. There were, however, no differences in the results whether moist or air dry samples were used for oven drying. The findings of Yoder that slaking is complete when a soil is air dried is not true for every soil and some soils will have to be subjected to oven drying or other treatments to obtain maximum slaking. The observation is in accordance with the results obtained by Woodburn (62) who also found that for complete slaking of Houston clay subsoil oven drying was necessary.

There was a decrease in aggregates larger than 0.2 mm. with a decrease in moisture (Fig. 1) but the extent of decrease was not the same in every soil. In Table 15 are given the figures for the aggregates larger than 0.2 mm. in soils wetted by capillarity and in air dry condition and the percentage decrease between the two.

The decrease in aggregates with a decrease in soil moisture varies greatly with the nature of the soil. In Geary silt loam subsoil there was a decrease of only 22.4 per cent but the silty clay loam surface soil from Hays showed a decrease of 88.9 per cent. The difference in aggregates larger than 0.2 mm. between the two soils in the wet condition was only 13.8 per cent but in the air dry soils it increased to 62.8 per cent. These results show that air drying brings about a decrease in water stable aggregates and it is different in different soils.

Furthermore, in field conditions soils never reach an air dry condition. Even under severe drought the top one or two centimeters of the soil may be reduced to an air dry moisture content while the soil below remains much above this moisture. Therefore, the results of aggregate analysis conducted on air dry soil do not give any idea of the size distribution of the aggregates under field conditions.

It has already been observed that change in size distribution of the aggregates in an air dry soil is brought about when a soil is submerged in water or when water is poured over the soil in large amounts because under these conditions air is trapped in

Table 15. A summary of the difference in aggregation found when air dry soils and soils that had been wetted by capillarity were analyzed.

Soil type	Total aggregates >0.2 mm. Wetted by capillarity	Total aggregates >0.2 mm. Air dry	Per cent decrease in aggregation
(1) Geary silt loam 0-7 inches	83.7	21.5	74.4
(2) Geary silt loam 8-14 inches	92.1	71.5	22.4
(3) Silty clay loam Hays 0-5 inches	78.3	8.7	88.9
(4) Silty clay loam Hays 6-10 inches	85.6	54.4	36.5
(5) Summit silt loam	36.6	8.8	76.0
(6) Parsons silt loam	82.4	25.1	69.6
(7) Woodson silt loam	80.7	15.9	80.3
(8) Summit silty clay loam	66.4	18.8	71.7
(9) Parsons silt loam	71.8	15.1	79.0
(10) Cherokee silt loam	57.2	20.7	63.9
(11) Labette silt loam	81.1	30.5	67.4
(12) Hays 65, silty clay loam, 3 inches	78.3	11.3	85.6
(13) Hays 66, silty clay loam, 9 inches	95.9	39.1	59.3
(14) Hays 67, silty clay loam, 18 inches	96.2	35.3	63.3
(15) Hays 68, silty clay loam, 3 inches	81.0	15.6	80.7

the soil pores and capillaries and shatter the soil aggregates in escaping. When the soils used in this investigation were wetted by capillarity, an atomizer, or under a vacuum, no shattering occurred as the air could escape. In actual farming practices soils are not always flooded with water. Flooding may be done under irrigated conditions but it is not of general occurrence in rain-fed areas. Therefore, it is not likely that shattering of aggregates by entrapping of air occurs under actual field conditions and analysis of air dry samples by submerging them in water, a process which is responsible for shattering of more than 60 per cent of the aggregates can not be expected to give a true picture of the aggregate status of the soil. It has probably been for this reason that several workers have found no correlation between the aggregates and performance of crops on different soils. Olmstead (41) has reported a detailed work on the aggregate analysis of plots at Fort Hays under different crops and system of rotations. He found no relation between the yield of crops and the amount of aggregates.

It has been reported (Tables 3 and 4) that slight changes in soil moisture content bring about a change in the size distribution of aggregates. Air dry moisture is not a constant figure. It varies with the condition of the atmosphere. Therefore, different aggregate analysis data may be obtained at different times. Seasonal variations in aggregates were observed by Wilson and Browning (60) and Alderfer (2) and these authors came to the conclusion that the moisture content of the soil had a definite influence on the size, amount, and distribution of soil aggregates but failed to find any simple relationship. These observations again point out the unreliability of the results obtained by the analysis of air dry sample.

Analysis of field moist samples has been suggested by Baver (3), Elson (16, 17), and Alderfer (2). The results obtained during the present investigation show that there was a much higher percentage of aggregates larger than 0.2 mm. in the field moist samples as compared to those analyzed in an air dry state. There is no doubt that the aggregate analysis of field moist samples will give a better picture of the state of aggregation of soil than the analysis of its air dry sample, but it can not always give the same amount of aggregates, because the amount of aggregates will vary with the moisture content of the soil (Table 3, Fig. 1). Comparative data may be obtained and the effects due to treatments may be brought out if the samples are at the same moisture content when analyzed, but this will not add much to the information which can be obtained by the analysis of air dry soil. The aggregate analysis results of two soils, even though they are at the same moisture content, can not be compared because the change in size distribution of aggregates at different levels of moisture is not constant (Fig. 1) in all soils.

The other important point which these results have brought out is that different results for aggregate distribution may be obtained even at the same moisture content of the same soil depending on the distribution of moisture in the capillaries. The results of wetting dry soils (Hays 65, 66, 67 and 68) in a humidor show that a maximum amount of aggregates larger than 0.2 mm.

was obtained in these soils at a moisture content of 16.3 per cent, which is much below their moisture equivalent of 34.6 per cent. The silty clay loam from Hays, 6-10 inches, with a moisture equivalent of 31.7 per cent gave a figure of 74 per cent for aggregates larger than 0.2 mm. at 16 per cent moisture as compared to 96.2 per cent obtained in the case of soils moistened to the same extent by keeping them in a humidor. Similar results were obtained by storing the soils in a moist condition in air tight containers. Although there was no change in the moisture content of the soil (Table 14), there was a definite change in the size distribution of aggregates. These results suggest that the wetting of the soil in a vapor phase affected better distribution of moisture in soil capillaries and replaced the air as effectively as wetting the soil by capillarity on moist sand or the removing of air by evacuation. Lebedeff (26) and other workers have shown that water distills from one layer of soil to another when differences in soil temperature exist. Therefore, changes noted in the laboratory can also occur in the field and a soil at the same moisture content may give two different size distributions of aggregates depending on the distribution of moisture in the capillaries. These results show that even the analysis of the soils in the field moist condition may not give an entirely true picture regarding the size distribution of aggregates under field condition.

It appears that the air in the soil capillaries is a limiting factor in the determination of water stable aggregates in the soil. Out of the different pretreatments of wetting tried, wetting of the soil by capillarity, wetting under a vacuum and wetting by an atomizer displaced the air without trapping it. Wetting by capillarity by placing the sample on wet sand gave the maximum amount of aggregates larger than 0.2 mm., and wetting under a vacuum closely followed it.

Wetting by an atomizer did not give constant results. The results varied with the texture of the soil. It gave as high aggregation as wetting by capillarity in the case of heavy textured soils and low aggregation in the case of light textured ones. These results are not in accordance with those reported by Russell (51) who found that wetting by an atomizer gave the highest results. In wetting by an atomizer the soil has to be turned over for getting uniform wetting and this mechanical turning might break some of the aggregates.

Of the remaining two treatments wetting under a vacuum gave more constant results, although slightly lower than those obtained by wetting by capillarity. As explained by Russell (51) in the soils saturated with water, the water molecules provide a dipole linkage that holds the soil particles together and make them resist the shearing action of water when shaken in it during analysis. This is in accordance with the observations made by Baver (3) and Bertramson and Rhoades (5) who have shown that soils at field moisture are better aggregated than air dried soils. According to McHenry et al. (29) the stability of Iowa soils decreased slightly and that of clay and sand mixtures decreased greatly when the moisture content became higher than the moisture equivalent. This suggests that there is no effect of adhesion of soil particles with films of water around them when soils are wetted under a vacuum. There might be some rupturing of soil aggregates due to swelling when the soils are wetted on sand but this aspect of the problem has not been studied. Addition of water to air dry soils that had been evacuated did not decrease the amount of aggregates in them, indicating that there is no breaking of aggregates by swelling when water is added to the soil under a vacuum. This observation, however, does not completely rule out the possibility of swelling of soil when wetted under a vacuum, although it can be said that its effects are small.

The above discussion of the results brings out that determination of aggregates in soils in an air dry state or in their field moist condition gives an arbitrary figure. To get comparable results the soils should be wetted by capillarity or under a vacuum. The choice of pretreatment depends on what is to be determined. If the absolute amount of aggregates is to be estimated without the introduction of another variable "water", wetting under a vacuum can be adopted. If the rupturing effect of air is to be eliminated but the effect of water in holding the soil particles together is to be measured, then wetting by capillarity can be used. In order to get maximum aggregation by capillary wetting, water should be allowed to rise slowly by keeping the soil over sand. Rapid wetting by keeping the soil in direct contact with a free water surface may lock up the air which, to escape, must disintegrate the aggregates and cause a decrease in the aggregates larger than 0.2 mm.

For the soils under study, wetting of soil under a vacuum gave more uniform and consistent results than wetting by capillarity, and the greatest difference recorded between the two methods was 9 per cent.

SUMMARY

Different methods have been used to evaluate the degree of aggregation or structural value of soils. Although a wet sieving technique is generally used for this purpose, results obtained with such techniques have not always been well correlated with field observations. Therefore, an investigation was conducted to determine what factors affect the results obtained in the wet sieve determination of water stable soil aggregates. The method of aggregate analysis tentatively recommended by the Soil Conservation Service and the Bureau of Plant Industry, United States Department of Agriculture, was used in the study.

The amount of aggregates larger than 0.2 mm. in diameter was found to decrease with a decrease in the moisture content of the soil, although the extent of the decrease differed with different soils. Even for the same soil there was no quantitative relationship between the decrease in moisture content and the decrease in aggregates larger than 0.2 mm.

The size distribution and total amount of aggregates in soils was not affected by the temperature of the water in the bath in which they were screened.

Slaking of some soils was not complete when they were in an air dry condition. Oven drying of these soils brought about a further decrease in the amount of water stable aggregates larger than 0.2 mm.

The effect of wetting air dry soils by different methods on the amount, size, and distribution of aggregates was investigated. Wetting the sample by immersing it in water or by pouring water on the soil caused air to be trapped in the soil capillaries. The entrapped air shattered the soil aggregates when it escaped and brought about a large reduction in the amount of aggregates larger than 0.2 mm. Wetting by capillarity over moist sand, pouring water on the soil after evacuating the air from it with a vacuum pump and wetting the sample by a fine spray from an atomizer displaced the air and resulted in an increase of from 22 to 89 per cent in the amount of aggregates larger than 0.2 mm. in size, as compared to those obtained in air dry samples without any pretreatment.

When soils were wetted by water vapor, less water was required to remove the air from the soil pores than when they were wetted by capillarity. Although soils contained much less moisture than their moisture-equivalent when wetted by water vapor, they gave as high a percentage of aggregates larger than 0.2 mm. as when they were wetted by capillarity to their moisture equivalent.

In the field moist samples, when stored in air tight containers, there was a great increase in percentage aggregates larger than 0.2 mm. during storage although there was a slight decrease in moisture. The increase was greater in the surface soil than in the subsoil. It was suggested that the increase in aggregation on storing moist samples was due to a redistribution of moisture in the samples.

A maximum amount of aggregates larger than 0.2 mm. was obtained from the wet sieve analysis when the samples were wetted by capillarity on moist sand. Wetting under a vacuum gave slightly lower results for aggregates larger than 0.2 mm. but gave more consistent results than wetting by capillarity.

The limitations of carrying on the wet sieve analysis of water stable aggregates on air dry and field moist samples have been pointed out. There is such a great decrease in the aggregates larger than 0.2 mm. when an air dry soil is used that it does not give any idea regarding the state of aggregation of the soil under field conditions. The decrease in the amount of aggregates larger than 0.2 mm. on drying of a soil is different in different soils, therefore, results of aggregate analysis of samples do not show the same relationship in air dry condition as in field moist condition. Analysis of field moist soils may give comparable results under a definite set of conditions, but like the analysis of air dry samples it also fails to give an accurate idea regarding the aggregate status of the soil under field conditions.

In order to obtain a fair estimate of the size distribution of aggregates in different soils, wetting of the sample by capillarity or under a vacuum is recommended.

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