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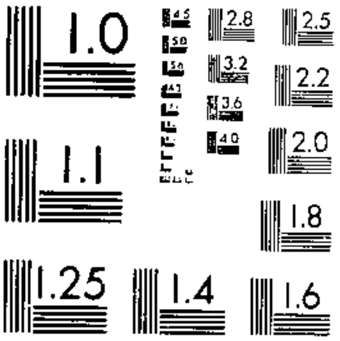

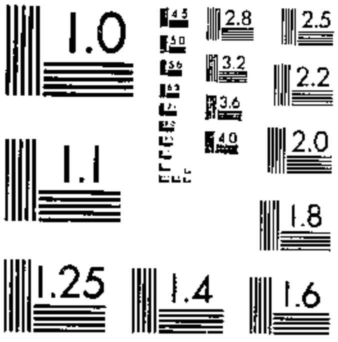

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BY

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SOME MOISTURE RELATIONS OF THE SOILS FROM THE EROSION EXPERIMENT STATIONS[1][2]

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CONTENTS

INTRODUCTION

A number of separate investigations are presented in this report because they all pertain to soil-moisture constants within the capillary range and because most of the soil samples used in each investigation were the profile samples of the erosion experiment stations of the Department of Agriculture. With the exception of the Marshall silt loam, all erosion station samples were taken from the same stock materials that were used by Middleton, Slater, and Byers (*23, 24, 30*),[3] who have published extensive studies of the physical and chemical properties of these soils and their extracted colloids.

The work on centrifugal moisture concerns the effect of high centrifugal forces on the moisture content of soils. This study was made possible by the development of a small moisture-equivalent type of centrifuge in which soil samples were subjected to forces as high as

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[1] Received for publication Jan. 25, 1937.

[2] This is the fifth report relevant to the properties and characteristics of the erosion station soils. The work presented in this report was initiated and completed before the transfer of the erosion stations to the Soil Conservation Service.

[3] Italic numbers in parentheses refer to Literature Cited, p. 42.

330,000 times that of gravity, a force much higher than previously had been used. In the study of the normal moisture capacity of soils, it was desired to obtain a laboratory soil-moisture test which would furnish a more accurate measure of the water-carrying capacity of field soils than does the moisture equivalent. The data may be of interest in connection with soil-erosion research.

A review of the literature on the sticky point reveals an unsatisfactory condition. Different operators may obtain widely different results by the same process upon the same soil, and one operator may obtain widely different results upon the same soil by the use of different procedures. In the study of the sticky point it was desired to develop a simple procedure that would depend upon personal judgment to a minimum extent only. The sticky point may be so defined and procedures for its determination so given that it is a property of only those soils in the plastic-consistence group of Atterberg. Since the lower plastic limit is also a property of plastic soils, the determination of this constant has been included in this work.

A number of determinations of the water-holding capacity of soils under various conditions of drainage and packing have been used. It seemed desirable to propose another test, the determination of the minimum percentage of water required to saturate a soil sample when it is arranged in closest packing but not subject to compression. Attempts were made to devise procedures that would accomplish this result.

The wide variety of data obtained for these soil samples in this and previous investigations appeared to be suitable for a study of the relationships of some of the moisture constants to each other and to other physical and chemical properties of the soils. Although only 52 samples and 11 profiles are represented in the group, they exhibit a wide range of physical and chemical properties. Conclusions drawn from a statistical study of such data appear more likely to be valid than when more samples and fewer of the great soil groups are used.

CENTRIFUGAL SOIL MOISTURE

The moisture retentiveness of soil under free gravitational drainage varies so greatly with changes in structure, packing, or other particle arrangement that it is practically impossible always to arrange loose soil material into a system physically comparable with the field soil in its water relations. Briggs and McLane (7) sought to obtain a system of packing laboratory samples to comparable conditions of capillary moisture by centrifuging thoroughly wetted soil samples. The percentage of water retained by the soil material under specified conditions in a centrifugal field 1,000 times the gravitational field of the earth (briefly 1,000 gravity) was called the moisture equivalent. This moisture constant has now become perhaps the best known and most used single-value soil property.

Lebedeff (*20*) studied the effect of higher centrifugal forces upon the moisture content of the wetted soil sample. He put small shallow soil samples into a small-diameter, high-speed centrifuge, and subjected them to centrifugal forces estimated to be as high as 70,000 gravity. He concluded that all capillary water was removed at about 18,000 gravity, and that none of the remaining water could be removed at higher gravitational fields. It was in part to check this surprising conclusion that this investigation was undertaken. The primary object was to determine whether it is possible by centrifugation to remove water from soils to a moisture content below the permanent wilting percentage, and to search for relationships between this moisture content, the moisture equivalent, and the water-vapor absorption at 99 percent relative humidity.

METHODS

The first centrifuge used in this work was made by mounting a small moisture-equivalent type of centrifuge head upon the shaft of the electric motor-driven, high-speed grinder used by Lebedeff (*20*). Heating of the soil samples due to air friction against the rotor was prevented by the use of an air-turbine head mounted directly beneath the centrifuge rotor so that the latter was bathed in an expanding jet of air. The turbine also furnished additional power and materially decreased the slippage of the driving belt. The centrifuge head, provided with a tightly fitting lid, held eight sample boxes, each of which was filled to a depth of 4 mm with soil material. The centrifuge radius was 38 mm to middepth of the samples. The rotor speed was checked with a stroboscope. Centrifugal forces as high as 100,000 gravity were obtained.

Because of bearing failures at the higher speeds this equipment was abandoned, and a bearingless centrifuge was used. Its construction was based upon the design of Beams and Weed (*5*). Weed furnished the stator and first rotor. The rotors finally used were of the design shown diagrammatically in figure 1. They were made from solid, heat-treated duralumin alloy 17ST, and were provided with tightly fitting screw-on lids. The inside diameter of the rotors was 1.25 inches, and the side walls were 0.10 inch thick. Sixteen equally spaced drainage holes 0.35 mm in diameter were drilled through the wall of each rotor perpendicular to the axis of rotation. The smooth inside walls were slightly concaved to facilitate drainage.

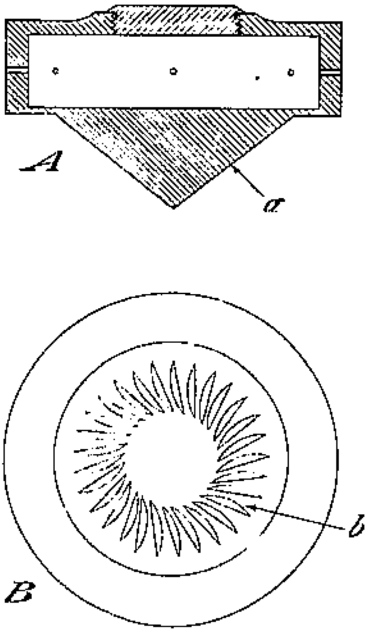

FIGURE 1.—Centrifuge rotor: *A*, side view; *B*, bottom view. The driving grooves, *b*, are located on the rotor nose at *a*.

The rotors were driven by compressed air striking the diagonally cut grooves milled into the conical noses. The stator, funnel-shaped and mounted vertically, contained the orifices of the driving air jets. When a rotor was placed upon the stator in the position shown in figure 2, and air pressure applied, the rotor lifted slightly and began to spin rapidly. The stator and rotor were enclosed in a felt-lined glass-covered container in order to reduce the intense high-pitched sound produced by some rotors, usually the least efficient ones. Many changes in design were made before rotors were obtained which were efficient and stable at all speeds. Subsequent to this investigation Garman (*14*) reported the essential conditions upon which may be based stator and rotor designs that provide the greatest stability and highest efficiency for this type of centrifuge. The rotational speeds were determined by means of a simple stroboscope made by mounting scanning disks having 80 holes or less upon the shaft of a variable-speed electric motor.

The rotor, which constituted a miniature single-sample moisture-equivalent centrifuge, was used also as sample box and weighing dish. The wall of the rotor was lined with a band of filter paper that had been moistened and then spun for a few seconds in order to hold it tightly in place. A sample equivalent to 4 g of oven-dry soil was poured into the rotor, moistened with distilled water, and allowed to stand for 3 to 5 hours. The rotor lid was then tightly screwed on and the sample spun at the desired speed for a definite length of time. The standard time was 20 minutes, and the standard speed was 2,315 revolutions per second, which produced a centrifugal force of 300,000 gravity at the middepth of the sample. After centrifuging, the loaded rotor was weighed, the lid removed, and the sample, still in the rotor, was dried at 105° C. overnight. For lack of a better term, the moisture content of the centrifuged sample so determined will hereafter be referred to as the "centrifugal moisture."

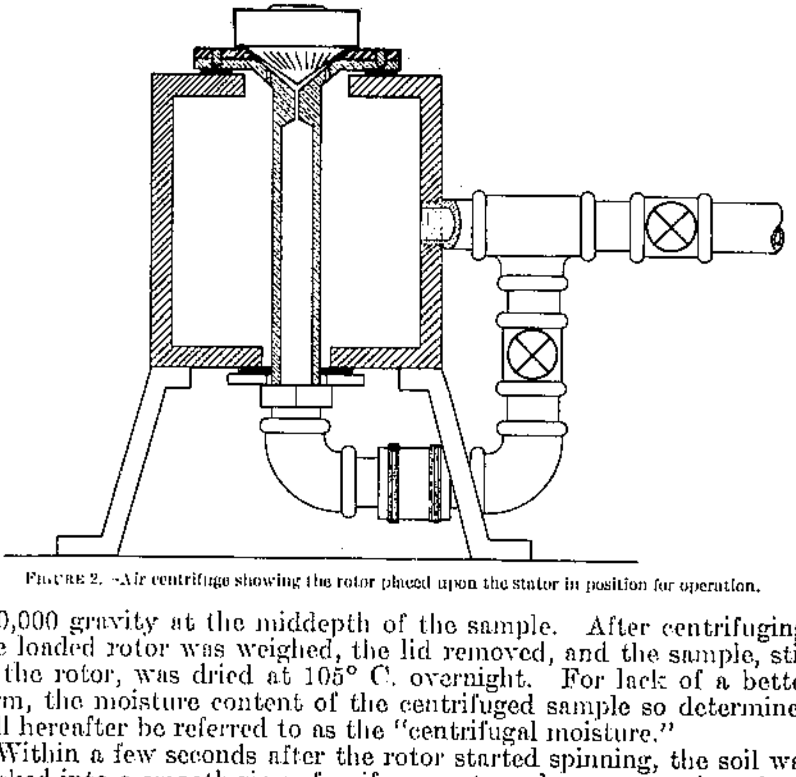

FIGURE 2.—Air centrifuge showing the rotor placed upon the stator in position for operation.

Within a few seconds after the rotor started spinning, the soil was packed into a smooth ring of uniform rectangular cross section about 4 mm thick against the rotor wall, where, after oven-drying, it remained as a hard dense mass except in the case of the very sandy soils. In clay soils high in organic matter, such as the Houston, shrinkage cracks occurred during drying. This soil also shrank away from the rotor, but most samples made a soil ring so firmly packed against the wall that they could be removed only by washing. A 4-g sample containing 10 percent of moisture exerts a force of nearly 1.5 tons in a field of 300,000 gravity and develops upon the walls of the rotor a pressure of about 2,000 pounds per square inch.

In the computation of the moisture content of the centrifugal sample, the small correction for the weight of the filter paper and the water it held was not made because of the uncertainty of the weight to be deducted. In one test the centrifuge was run at standard speed containing at first only a heavy wet filter band and later the same band backed by 2 g of wet sea sand. The water held by the filter alone in the first instance was greater than that held afterward by the sand and filter combined. In this work a thin hard filter band was used that weighed only 0.025 g and was just wide enough surely to cover the small drainage holes in the rotor wall. The weight ratio of filter to soil was about the same as exists in standard moisture-equivalent determinations.

Since this type of centrifuge has not hitherto been used for centrifuging soil samples, details of operation and other observations may be of interest. The loaded rotors developed centrifugal forces of 300,000 gravity with a driving air pressure of about 110 pounds per square inch, forces of 200,000 gravity at half that pressure, and forces of 20,000 gravity at only 5 pounds per square inch above atmospheric pressure. Manual control of the air pressure was relied on to keep the centrifuge speed in synchronism with the stroboscope. This method of control was adequate at high speeds but not at the lower ones. It may be observed in figure 3, *B*, that, at high speeds, variations in centrifugal forces, easily within control, produce small changes in moisture content of the centrifuged sample, but that at low speeds this is no longer true. The determinations made at low centrifugal forces were not accurate in comparison with moisture-equivalent determinations at 1,000 gravity, but at full speed duplicates agreed quite as well as do standard moisture equivalents.

The time interval for centrifuging was made rather short in order to minimize the possibility of drying the sample by a flow of air through the rotor. The lids, screwed on with a fine thread, made contact with the top of the rotor so that they fitted tightly. Whether they remained tight at 2,300 revolutions per second is uncertain. At that speed, due to centrifugal force, an air-pressure difference of about 4 pounds per square inch existed between the edge of the lid and the drainage holes in the side wall of the rotor. The drainage holes were so small that no great flow of air through the sample was possible. Repeated centrifugings gave only small losses in weight. Rotors with only 2 drainage holes gave a few tenths of a percent higher soil moistures than those with 8 or 16 holes.

With the equipment available it was necessary to keep the rotor diameter small if high centrifugal forces were to be obtained. Lower soil moistures could have been obtained in the centrifuged samples by increasing the sample depth, but because the rotor radius was only 15.9 mm, the sample depth was limited to 4 mm. A radius of 13.9 mm was used in computing centrifugal forces.

Even at this sample depth there was some difficulty in securing drainage in centrifuged samples of the lower profile layers of some of the silt loams, particularly the Shelby. Drainage was freer in the Houston, the heavy-textured lateritic samples, and even in the extracted lateritic colloids. For samples which presented this difficulty, the centrifuge was run at very slow speed for the first minute or two. Then the speed was increased so gradually that most of the excess water was removed before the sample was firmly compacted against the rotor wall. In a few cases water was removed from the rotor with pieces of filter paper until no more free water appeared when the centrifuge was run several minutes at 150,000 gravity. The sample was then run for 20 to 30 minutes at 300,000 gravity. If the moisture contents of replicate samples agreed and were consistent with those obtained for other samples of the profile, the results were assumed to be correct.

Centrifuges of this type are inexpensive and easily built. They have no bearings and consequently are not heated by bearing friction. Nor are the rotors heated by air friction, because they are bathed in expanding jets of air. The sample is held at a nearly constant temperature of perhaps 5° to 10° below that of the room.

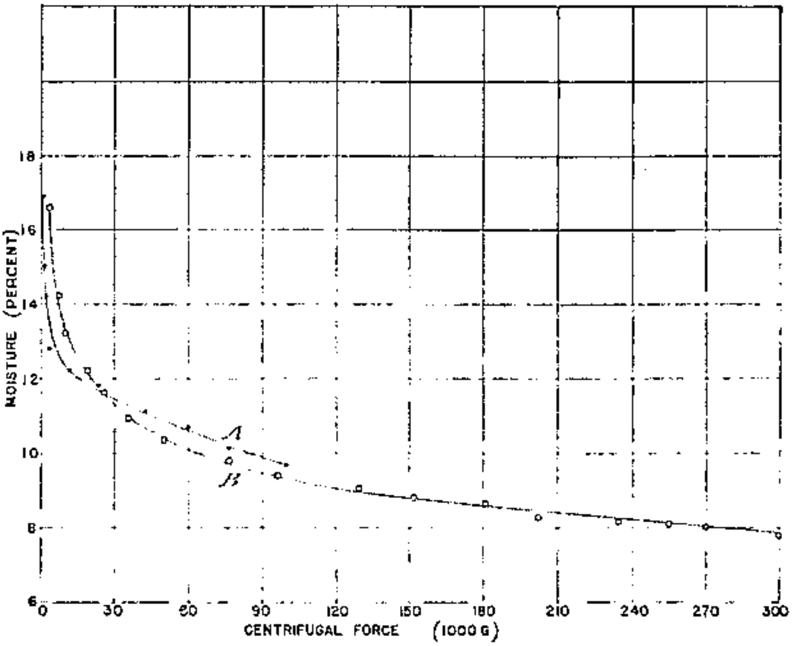

FIGURE 3.—Relation between moisture content and centrifugal force for sample no. 6720: *A*, 1.25-g samples in Lebedeff-type electric motor-driven centrifuge; *B*, 4-g samples in Beams-type air-driven centrifuge.

RESULTS

The relation of moisture content to the centrifugal force applied is shown in figure 3 for the B horizon of the Vernon fine sandy loam. The data for figure 3, *A*, were obtained by centrifuging 1.25-g samples in the Lebedeff-type electric motor-driven centrifuge; the data for *B* were obtained with 4-g samples in the Beams-type air-driven centrifuge. In both cases the samples were about 4 mm thick. The moisture content at 300,000 gravity was 7.8 percent, a value somewhat higher than the value for water-vapor absorption at 99 percent relative humidity, which was 6.4 percent. The moisture equivalent, 17.7 percent, was reached at about 2,500 gravity with the air-driven centrifuge and at 1,700 gravity with the motor-driven one, the latter providing the better drainage at slow speeds. The permanent wilting percentage, which was not determined for this soil but computed from the Briggs and Shantz equation (*8*), is 9.6 percent. To obtain this moisture content, the sample would have to be run in the air-driven centrifuge at about 85,000 gravity.

These data do not support Lebedeff's conclusion that at 18,000 gravity all capillary water is removed from soils. The change in curvature of graph *A* is not great at forces above 18,000 gravity, but neither graph indicates that the limit of water removal by centrifugal force has been reached. The shapes of curves such as these depend upon the type of centrifuge, depth of sample, and procedures employed, as well as upon the soil sample itself.

Data on the centrifugal moisture of some soil materials are given in the tabulation below. These determinations were made with a rotor of 1-inch inside diameter, run at 330,000 gravity. All except the peat were 2-g samples, and their depth was about 2 mm. The dried peat, ground to pass a 2-mm sieve, was as large a sample as could be used. Its weight was 0.9 g, and its moisture equivalent was 169 percent. The material was obtained from the surface layer of a sawgrass peat profile at Belle Glade, Fla. The profile description is given by Feustel and Byers (*12*). The three soil colloid samples were extracted from the A_1, A_2, and A_3 horizons of the Columbiana clay, an aluminous laterite from Costa Rica. A profile description and other data pertaining to this soil are given by Byers, Alexander, and Holmes (*10*). The water-vapor-absorption values of the three samples at 99 percent relative humidity were 27.4, 29.3, and 30.2 percent, respectively.

Samples:	*Centrifugal moisture percent*
No. 4 sand (0.25–0.10 mm)	1.32
No. 5 sand (0.10–0.05 mm)	1.5
Silt (0.05–0.005 mm)	1.6
Quartz flour, silt size	1.2
Quartz flour, mixed sizes	3.6
Peat (sawgrass)	56.0
Soil colloid no. 9801	30.0
Soil colloid no. 9805	31.1
Soil colloid no. 9806	31.7

The sands and silts were composites of soil separates obtained in the course of routine mechanical analysis. The silt was coarse, the finer portion having been removed with the clay. This material had been treated with hydrogen peroxide in order to oxidize the organic matter, and then shaken in a 0.05 N sodium oxalate solution to remove colloid coatings.

The ground quartz consisted almost entirely of particles of silt and clay sizes. The moisture equivalent of the mixture was 26 percent; that of the silt fraction, 25 percent. The great differences between the quantity of water held at 1,000 and 300,000 gravity most likely were due to the particle-size distribution. The particle-size distribution of this sample produced many voids which held water against a force of 1,000 gravity but which drained in the higher centrifugal field.

TABLE 1.—*Centrifugal moisture of soils and other related data*

Soil sample no.	Silt 2μ-50μ	Very fine silt 2μ-5μ	Clay >2μ	Centrifugal moisture	Moisture equivalent	Water-vapor absorption	Ratio of water-vapor absorption to clay	Ratio of centrifugal moisture to—		
								Clay	Water-vapor absorption	Moisture equivalent
COLBY SILT LOAM, HAYS, KANS.										
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*				
6842	49.0	3.8	30.2	10.7	27.3	9.6	0.32	0.35	1.12	0.39
6843	47.0	5.6	32.4	11.1	25.2	9.1	.28	.34	1.21	.44
6844	55.4	8.4	30.3	10.8	24.1	8.6	.28	.36	1.25	.45
6845	57.3	9.0	28.6	10.6	23.6	8.7	.30	.37	1.22	.45
6846	60.1	9.3	29.0	10.8	24.8	8.9	.31	.37	1.21	.44
6847	55.6	8.9	26.8	9.4	23.7	7.9	.29	.35	1.19	.40
HOUSTON BLACK CLAY, TEMPLE, TEX.										
6096	41.5	15.5	44.9	15.1	30.6	12.2	0.27	0.31	1.23	0.50
6097	42.6	17.5	40.6	16.5	27.6	12.0	.30	.35	1.38	.60
6098	44.7	17.6	44.1	13.1	24.4	10.6	.24	.30	1.23	.54
6099	49.4	18.4	36.2	11.1	20.6	8.0	.22	.31	1.39	.54
MARSHALL SILT LOAM, CLARINDA, IOWA										
B171	61.9	2.9	32.4	10.4	30.1	8.6	0.27	0.32	1.21	0.35
B172	61.3	4.8	34.6	13.1	31.8	10.2	.30	.38	1.28	.41
SHELBY SILT LOAM, BETHANY, MO.										
6797	47.2	2.7	21.3	8.7	21.5	6.0	0.28	0.36	1.26	0.36
6798	30.2	3.1	48.7	17.5	31.9	14.8	.30	.36	1.18	.55
6799	33.3	4.8	45.4	17.0	31.2	14.7	.32	.37	1.15	.55
6800	30.9	4.0	37.8	12.9	27.1	11.1	.29	.34	1.16	.48
6801	35.1	6.8	29.7	10.5	23.1	8.0	.27	.35	1.31	.46
6802	35.7	6.2	31.0	9.4	22.9	8.0	.26	.30	1.18	.41
6802A	19.6	3.2	18.5	6.2	16.1	4.9	.26	.34	1.26	.39
6802B	34.7	5.6	30.0	9.2	23.5	8.1	.27	.30	1.13	.39
CLINTON SILT LOAM, LA CROSSE, WIS.										
10362	80.6	7.9	11.2	5.4	23.9	4.1	0.37	0.48	1.32	0.23
10363	74.0	6.5	18.8	7.8	23.5	6.0	.32	.41	1.30	.33
10364	71.0	5.2	21.8	8.9	24.7	7.4	.34	.41	1.20	.36
10365	70.7	4.2	18.2	7.8	22.4	6.3	.35	.43	1.24	.35
10366	9.4	1.8	21.4	7.7	13.8	5.9	.28	.36	1.31	.56
PALOUSE SILT LOAM, PULLMAN, WASH.										
8069	67.5	3.5	21.0	9.6	25.1	7.9	0.33	0.40	1.22	0.38
8070	59.2	3.7	33.8	13.6	27.8	10.6	.31	.40	1.28	.49
8071	61.6	3.4	32.0	13.5	27.6	10.7	.33	.42	1.26	.49
8072	60.2	3.2	26.6	10.9	25.5	9.1	.34	.41	1.20	.43
8073	67.3	3.3	25.0	10.0	25.5	9.2	.36	.39	1.09	.39
VERNON FINE SANDY LOAM, GUTHRIE, OKLA.										
6718	21.0	2.8	5.2	2.7	9.6	2.2	0.42	0.52	1.23	0.28
6719	15.0	2.1	9.9	3.3	9.1	2.5	.25	.33	1.32	.36
6720	15.5	8.2	23.8	7.8	17.7	6.4	.27	.33	1.22	.44
6721	39.6	4.8	27.4	8.0	18.4	5.8	.21	.29	1.38	.43
MUSKINGUM SILT LOAM, ZANESVILLE, OHIO										
B407	71.7	8.6	19.9	7.6	25.5	6.3	0.32	0.38	1.21	0.30
B408	63.0	9.8	27.3	9.6	26.2	9.1	.33	.35	1.05	.37
B409	53.4	9.5	25.3	8.6	21.0	8.2	.32	.34	1.05	.41
B410	51.5	8.0	20.3	6.2	19.4	5.7	.28	.31	1.09	.32
B411	63.0	11.4	19.0	5.7	19.8	5.2	.27	.30	1.10	.29

TABLE 1.—*Centrifugal moisture of soils and other related data*—Continued

KIRVIN FINE SANDY LOAM, TYLER, TEX.

Soil sample no.	Silt 2μ-50μ	Very fine silt 2μ-5μ	Clay $>2\mu$	Centrifugal moisture	Moisture equivalent	Water-vapor absorption	Ratio of water-vapor absorption to clay	Ratio of centrifugal moisture to—		
								Clay	Water-vapor absorption	Moisture equivalent
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*				
6678	18.4	2.9	5.6	2.5	7.9	1.8	0.32	0.45	1.39	0.32
6679	8.8	1.6	59.4	16.9	30.5	16.9	.28	.28	1.00	.55
6680	13.0	3.4	50.0	15.3	28.5	14.8	.30	.31	1.03	.54
6681	16.3	3.1	32.3	9.2	21.2	9.8	.30	.28	.91	.43
6682	4.7	1.9	7.3	3.0	6.7	3.0	.41	.41	1.00	.45

NACOGDOCHES FINE SANDY LOAM, TYLER, TEX.

Soil sample no.	Silt 2μ-50μ	Very fine silt 2μ-5μ	Clay $>2\mu$	Centrifugal moisture	Moisture equivalent	Water-vapor absorption	Ratio of water-vapor absorption to clay	Clay	Water-vapor absorption	Moisture equivalent
9475	41.7	1.9	16.1	6.5	14.3	5.5	0.34	0.40	1.18	0.45
9476	9.2	1.8	47.1	15.4	25.2	15.0	.32	.33	1.03	.61
9477	6.6	.7	38.2	15.6	25.1	15.6	.41	.41	1.00	.62
9478	3.4	2.0	31.7	9.9	18.6	9.8	.31	.31	1.01	.53
9479	6.0	1.3	32.7	13.3	22.5	13.5	.41	.41	.99	.59

CECIL SANDY CLAY LOAM, STATESVILLE, N. C.

Soil sample no.	Silt 2μ-50μ	Very fine silt 2μ-5μ	Clay $>2\mu$	Centrifugal moisture	Moisture equivalent	Water-vapor absorption	Ratio of water-vapor absorption to clay	Clay	Water-vapor absorption	Moisture equivalent
6977	28.4	8.2	17.3	7.7	20.0	6.0	0.35	0.45	1.28	0.39
6978	17.5	5.5	51.2	14.8	26.6	13.6	.27	.29	1.09	.56
6979	25.3	8.2	48.6	15.6	28.7	14.9	.31	.32	1.05	.54

Table 1 presents the results of centrifugal-moisture determinations and other pertinent data of profile samples taken from the soils of the erosion experiment stations. The soil profiles have been described by Middleton, Slater, and Byers (*23*, *24*). The moisture equivalents are taken from their data, and the silt and clay percentages were computed from their mechanical-analysis data. Throughout this bulletin the material below 2μ in diameter is designated as clay, and the material between 2μ and 50μ in diameter as silt. The centrifugal-moisture determinations were made with rotors 1.25 inches in inside diameter at 300,000 gravity.

From the data presented in the tabulation on page 7 it is apparent that in the case of the soils of table 1 only a small portion of the centrifugal moisture is held in narrow contact angles between the mineral grains and in interstices with fine capillary openings. If the greater part is held in some manner by the colloid fraction, the centrifuged moisture may be expected to show some relationship to the content of fine material in the soil and to other soil moisture constants which are related to soil texture.

It may be noted from table 1 that the ratio of centrifugal moisture to clay content is high in the sandy surface layers. This is due in part at least to the fact that the clay content was determined upon samples from which the organic matter had been removed, whereas the centrifugal moisture was determined upon all the soil material which passed through a sieve with 2-mm round holes. If the percentage of organic matter in the surface layer is added to the clay content, then the ratios fall in line with the values for the lower layers. The average value of the centrifugal moisture-clay ratio is

0.36, with an average deviation of 11 percent. If the organic matter is included in the clay, the ratio becomes 0.35, with an average deviation of 10 percent. The ratio of clay to water-vapor absorption is 0.31, with an average deviation of 11 percent. If these samples are typical of soils in general, then the centrifugal moisture furnishes as reliable a measure of the clay content as does the determination of water-vapor absorption at 99 percent relative humidity.

Figure 4, which is a scatter diagram of the centrifugal moisture plotted against water-vapor absorption at 99 percent relative humidity, shows that the former has a slightly higher average value. The diagonal straight line is the locus of all points of equal values of the two constants. Below this line the centrifugal moisture is higher than the water-vapor absorption. In the two instances in which the centrifugal moisture is less than the water-vapor absorption, the results are not necessarily in error. The capillary tension computed on the pF scale of Schofield (*27*) is 5.1 for the centrifugal moisture and only 4.15 for the water-vapor absorption. The reason why all the centrifugal-moisture results are not lower will be discussed later. The average value of the ratio is 1.19, with an average deviation of 8 percent.

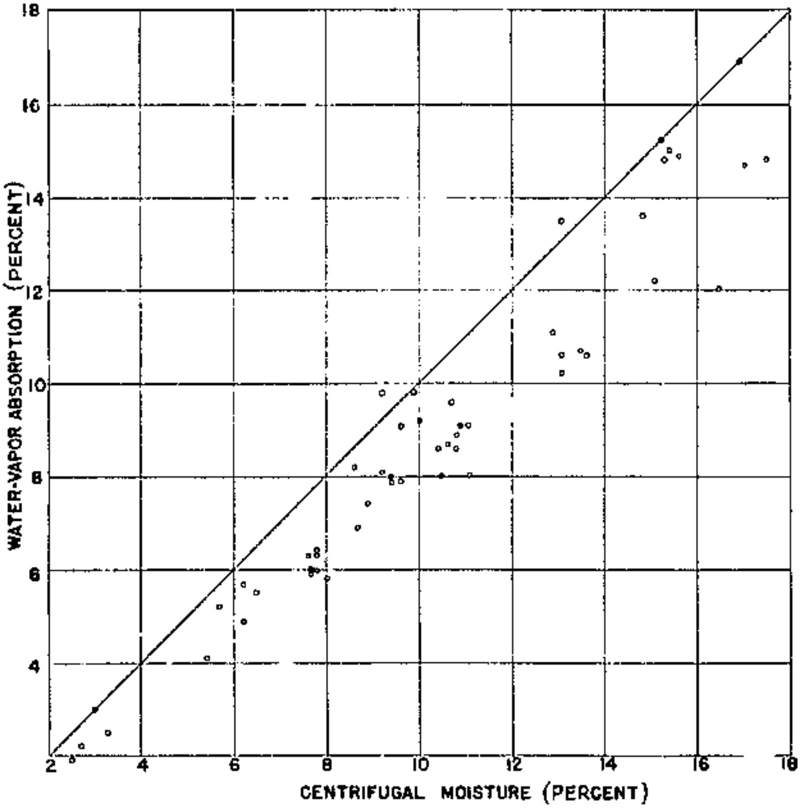

FIGURE 4.—Scatter diagram showing the relation of centrifugal moisture to the water-vapor absorption at 99 percent relative humidity.

TABLE 2.—*The silica-sesquioxide ratios and the centrifugal moisture-water-vapor absorption ratios for the soil-profile samples*

Soil	Mol ratio[1] $\frac{SiO_2}{R_2O_3}$	Ratio of centrifugal moisture to water-vapor absorption	Soil	Mol ratio[1] $\frac{SiO_2}{R_2O_3}$	Ratio of centrifugal moisture to water-vapor absorption
Colby	3.60	1.22	Vernon	2.38	1.31
Houston	3.25	1.33	Muskingum	2.11	1.08
Marshall	2.90	1.28	Kirvin	1.81	1.09
Shelby	2.65	1.29	Cecil	1.35	1.07
Clinton	2.64	1.26	Nacogdoches	1.25	1.09
Palouse	2.52	1.22	Columbiana	.90	1.07

[1] Profile averages.

In table 2 are given the profile averages, omitting the sandy surface layers, of the ratios of centrifugal moisture to water-vapor absorption at 99 percent relative humidity, arranged in decreasing order of the average silica-sesquioxide ratios of the extracted colloids. The moisture ratio for the Columbiana is not strictly comparable because the centrifugal moisture was determined on a layer only 2 mm thick, run in a rotor 1 inch in inside diameter at 330,000 gravity. In other instances, samples 4 mm thick run at 300,000 gravity gave a few tenths of a percent lower moisture content. The moisture ratio for the colloid should no doubt be lower, but its exact value is unimportant here. This ratio serves to divide the soils into two groups. In one group, having ratios between 1.22 and 1.33, are the soils with the higher silica-sesquioxide ratios. In the other group the soils are all lateritic, except the Muskingum. It has a lower silica-sesquioxide ratio, lower pH value, lower exchangeable-base content, and lower exchange-base capacity than any of the soils of the other set, which belong to the Gray-Brown Podzolic, Prairie, Rendzina, and Chernozem groups. The ratio of moisture equivalent to water-vapor absorption is also lowest in the lateritic soils. One possible explanation of this group separation is that the most lateritic profile layers do not deflocculate so readily as those of the other soils and consequently drain better in the centrifuge. The division of these soils into two groups, based upon the ratio of centrifugal moisture to water-vapor absorption, may not be significant, but it seems quite likely to be a physical confirmation of the fact that wide chemical differences exist between the colloids of the two groups.

RELATION OF CENTRIFUGAL MOISTURE TO MOISTURE EQUIVALENT AND PERMANENT WILTING PERCENTAGE

Because of the interest of agronomists in the relationships of the permanent wilting percentages (p. w. p.) to moisture equivalent (m. e.), a brief examination of the relation of these constants to centrifugal moisture (c. m.) will be made. Briggs and Shantz (*8*) found that within rather narrow limits p. w. p./m. e.=0.543, the reciprocal of 1.84. Thomas (*31*) obtained an average value of 0.42 for three samples. Work and Lewis (*35*) made 49 determinations of the permanent wilting percentage and of the moisture equivalent of a heavy clay adobe soil. The ratio p. w. p./m. e. ranged between the limits 0.382 and 0.521. The average value was 0.455. Feustel and Byers (*13*) determined this ratio for three samples of peat and for mixtures of the peats with a clay loam, a loamy fine sand, and a pure quartz sand. The ratios ranged from 0.32 to 0.79, with an average of 0.473. Veihmeyer and Hendrickson (*34*) found that for over 100 soils for which they had made the determinations, the value of p. w. p/m. e. ranged from 0.262 to 0.719.

From these investigations it is clear that the permanent wilting percentage bears no definite relation to the moisture equivalent, and from the data of table 1 it may be inferred that no definite ratio is to be expected. The top and bottom layers of the Clinton profile furnish an illustration of the fact that from the moisture content of a soil at one capillary tension one cannot predict what the moisture content will be at another tension. The surface layer of the Clinton has 19.1 percent of material below 5μ in diameter. The bottom layer has 23.2 percent of such material—only a slightly greater amount. The remaining material is mostly sand in the lower layer and almost entirely silt in the upper one. The particle-size distribution of the silty surface layer produced a structure whose pore spaces held 23.9 percent of water at 1,000 gravity, whereas the larger voids of the sandy clay layer beneath held slightly more than half as much moisture under the same conditions. At 300,000 gravity the moisture ratio is very different. Here the moisture content is controlled to a greater degree by the clay content, which is nearly twice as high in the sandy layer as in the silty one. The ratio c. m./m. e. is 0.23 in the surface layer and 0.56 in the lowest one. For the silt-sized ground quartz the ratio is 0.05. There is a high correlation between the c. m./m. e. ratio and the clay content of the soils of table 1. This correlation may be due in part to differences in the packing of the samples in the two centrifuges.

An ideal case, suggestive of possible variations in moisture content at the two centrifugal forces, is that of an ideal soil consisting of uniform spheres 42μ in diameter arranged in closest packing. If the ordinary laws of capillarity are assumed and the adsorbed surface films neglected, the voids in this case once filled would remain full of water in a field of 1,000 gravity. At 300,000 gravity the water rings about the points of contact of the spheres would become so small that they would occupy only 0.02 percent of the total volume of the voids.

During centrifuging, the moisture content of the soil sample in contact with the rotor wall may be high, perhaps approaching saturation. The negative moisture gradient directed toward the inner surface is such that at equilibrium the capillary tension is just balanced by the centrifugal field. The centrifugal force upon the water of the sample spinning in the small air-driven rotors at 2,315 revolutions per second is 5.1 on the Schofield pF scale (*27*), assuming no potential exists at the outer boundary. According to Schofield, a soil under this high capillary tension should be in thermodynamic equilibrium with an atmosphere at 92 percent of saturation. Consequently it might be assumed that the centrifugal moistures should be considerably lower than the water-vapor absorptions given in table 1. In water-vapor absorption determinations the atmosphere is maintained at a relative humidity of 99 percent, which corresponds to a pF of only 4.15.

The apparent reasons why the centrifuge usually yielded higher soil moistures than the water-vapor absorption are that the former is a drying process, the latter is a wetting process, and none of the results obtained were equilibrium values. The water-vapor absorption is determined in this laboratory by exposing a dry soil sample, held at constant temperature, to an atmosphere of 99 percent relative humidity for 5 days. This interval of time is sufficient for the absorption of water vapor to become relatively slow, but not complete. In only 20 minutes, centrifugation can do no more than reduce the capillary movement of water to a relatively low value, and the time is too short for any appreciable movement of water in the vapor phase. These two moisture constants are near the upper limit of the hygroscopic moisture range, in which the capillary movement of water is very slow. The movement of soil water in either the liquid or vapor phase and in any moisture range becomes very slow as equilibrium is approached. The thermodynamic equations from which the pF values are computed assume true and reversible equilibrium conditions. Equilibrium conditions of soil moisture probably are never realized, as such experiments as those of Veihmeyer (*32*) or of Shreve and Turnage (*29*) indicate.

Estimates of the capillary tension of the soil at the permanent wilting percentage range from about 4 to 25 atmospheres. Veihmeyer and Hendrickson (*34*), who have made a thorough study of the wilting of plants, found evidence of permanent wilting when plant roots were put into solutions having osmotic pressures of about 16 to 20 atmospheres. These tensions on the pF scale range from 4.22 to 4.32, values only slightly greater than the water-vapor absorption at 99 percent relative humidity. Because the latter is a wetting process and the former is a drying one, the soil may be expected to have the higher moisture content at the permanent wilting percentage. Sufficient quantities of these samples were not available for wilting-point determinations, and so the relation of centrifugal moisture to the permanent wilting percentage is not definitely known. But from the known relations of each of the two moisture constants to the moisture equivalent, it is apparent that the centrifugal moisture value is considerably lower than the permanent wilting percentage.

Due to column-end and packing effects, the moisture content of a soil at permanent wilting will certainly be lower than that of the same soil centrifuged at the same capillary tension. After the water has ceased to drain from a percolating soil column there should exist within it a zone whose height and moisture content do not differ greatly from those which would obtain in the same soil after a capillary rise from a free water surface. The sample in the moisture-equivalent centrifuge is virtually a percolating soil column. In the small high-speed rotors the column is short, about 4 mm, and the soil is packed against a hard filter band or the smooth wall of the rotor, which has only a few small drainage holes covered with the filter band. These conditions are favorable to the retention of water and account in part for the fact that samples run in these rotors at 1,000 gravity have a moisture content somewhat higher than the moisture equivalent.

The small high-speed rotor produces a smaller volume of voids than does the moisture-equivalent centrifuge. The pressure per unit of surface area of the sample against the container wall at 300,000 gravity is of the order of 100 times that which occurs in standard moisture-equivalent determinations. The initial high fluidity of most samples is also favorable to close packing, which enables the soil to retain more capillary water at high capillary tensions than might be expected from centrifugation at 1,000 gravity.

In determinations of permanent wilting percentages the soils are drained by an internal absorbing system that is not subject to column-end and packing effects. If the centrifuge were to be used successfully as an instrument for the indirect determination of permanent wilting percentages, it seems certain that higher tensions would be required than are now developed in moisture-equivalent determinations. If the centrifugal force were increased the soil packing would be increased also. This packing would not interfere with the accuracy and reliability of the method if it had relatively the same influence upon all soils. It seems unlikely that the packing effect would be a constant factor, but the variations might not be so large for forces of the order of 10 to 20 atmospheres as to introduce prohibitively large errors in the determinations. From the data obtained in this investigation it seems likely that the most nearly constant ratio between centrifugal moisture and permanent wilting percentage would be obtained from the operation at several thousand gravity of a centrifuge which, at 1,000 gravity, would yield a soil-moisture content equal to or less than the moisture equivalent. This latter condition can be satisfied by the use of a sample box providing as free drainage as possible for a soil sample the depth of which is equal to or greater then the depth of the sample employed in moisture-equivalent determinations.

NORMAL MOISTURE CAPACITY

The term "normal moisture capacity" was coined by Shaw (*28*) to designate the "minimum amount of water that is retained by absorption and film forces when the water is free to move downward through a mass of uniform soil." The procedure employed in this investigation was somewhat similar to the one used by Shaw, and for this reason, the name is retained. In this work the term "normal moisture capacity" is applied to the moisture content of a wet soil in contact with a dry layer after the movement of capillary water becomes very slow. In these experiments the wet layer initially had some gravitational water and the dry layer only hygroscopic moisture. The purpose of the investigation was to ascertain, if possible, what relation this moisture constant bears to the field capacity and to other physical and chemical characteristics of the soils under investigation.

PROCEDURE

The following procedure for the determination of the normal moisture capacity was employed. The sample was prepared by passing the soil material through a 2-mm round-hole sieve and then by further breaking apart the aggregates to pass a similar 1-mm sieve. The sample, while being stirred and turned with a spatula, was moistened with a fine spray from an atomizer until the material just ceased to be dusty. This degree of granulation appeared to be helpful in preventing segregation of the fine from the coarse particles during the filling of the soil tubes. The tubes, of pyrex glass, were 2 inches in inside diameter and 20 inches long. Each was equipped with two rubber stoppers having capillary openings, which served the purposes of equalizing the air pressure and preventing the loss of soil water by evaporation. The tubes were filled with the prepared soil material and packed with a rotary compactor to a depth of 18 inches. The apparent volume, initial moisture content, and weight of the soil material in each tube were recorded in order to compute the volume weight.

In wetting the soil column by the addition of distilled water drop by drop from a burette or through a capillary tube, an attempt was made to control the rate of flow so that the soil column was not flooded at any time. The soil surface was covered with a fine screen to prevent puddling. The desired quantity of water, which required from perhaps 2 hours to as long as 5 days for its reception, was such as would wet the soil column to a depth of about 15 inches within a week after its addition. As soon as the addition of water ceased, the soil tubes were stoppered, placed in an upright position in a lightproof wooden box, and then stored in the laboratory.

In these experiments two tubes were filled with each soil. One was stored with the dry end at the bottom so that the capillary movement was downward. The other tube was reversed so that the capillary movement was upward. After standing for 7 days the entire soil column was sampled in 1-inch sections with a core sampler made of a thin metal tube of one-half inch inside diameter. These core samples were dried overnight, and the moisture contents determined.

RESULTS

The moisture distribution and initial moisture content of the Palouse silt loam profile samples are presented in table 3. In figure 5 the moisture distribution is shown graphically for four soil samples ranging in texture from a fine sandy loam to a heavy clay. These data, which are typical, show that in each soil column there is only a slight decrease in moisture content from 1 or 2 inches below the surface down to within a few inches of the dry layer. In the lower portion of the moistened section there is a rapidly decreasing moisture content as the dry layer is approached. The data of Shaw (*28*) show even better the same characteristic moisture distribution. The more nearly perfect uniformity of moisture content in Shaw's samples may be due to the differences in method of packing or sampling, in the size and length of the soil columns, in the time allowed for moisture distribution, or in the more favorable texture of his sample.

TABLE 3.—*Moisture distribution resulting from downward and upward capillary movement of water in samples of Palouse silt loam*

Depth (inches)	No. 8069		No. 8070		No. 8071		No. 8072		No. 8073	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0-1	26.7	27.4	28.7	31.9	30.2	33.3	26.8	28.4	26.5	28.6
1-2	24.9	25.6	26.4	29.5	32.2	29.7	24.8	26.8	25.1	26.1
2-3	24.9	25.4	26.2	28.4	28.0	28.7	24.0	26.2	24.7	25.6
3-4	24.3	25.0	26.0	25.4	27.0	28.1	23.8	25.5	24.3	24.4
4-5	24.1	25.9	25.0	28.2	26.7	28.1	23.6	25.2	24.0	23.8
5-6	24.0	25.5	25.8	27.6	26.5	27.5	23.3	24.6	23.6	23.2
6-7	23.7	25.8	25.6	27.3	26.2	28.2	22.7	24.3	23.1	22.3
7-8	23.4	24.7	25.2	26.9	26.1	27.7	22.3	24.4	23.4	21.7
8-9	23.1	24.3	25.3	26.5	26.3	27.8	22.0	24.3	23.4	21.6
9-10	22.0	23.7	24.4	26.8	26.2	27.3	21.0	24.1	22.8	21.1
10-11	21.1	23.3	23.9	26.3	25.8	26.8	19.9	23.6	22.3	19.5
11-12	20.0	22.5	21.9	25.3	24.8	26.0	15.2	23.0	21.1	18.1
12-13	18.6	21.3	20.3	24.3	23.5	25.1	15.2	21.9	20.0	17.4
13-14	16.6	19.8	15.8	22.0	22.0	23.5	7.1	20.7	18.7	8.3
14-15	8.7	18.5	8.3	19.9	20.1	21.7	5.7	19.5	16.9	5.8
15-16	5.2	16.2	7.0	11.3	12.4	17.7	5.4	17.9	10.0	6.0
16-17	4.8	6.7	7.0	7.1	7.9	8.4	5.1	9.5	5.7	5.6
17-18	4.8	5.6	6.0	6.7	7.5	7.8	5.2	6.7	5.4	5.5
	[1] 4.6	[1] 5.1	[1] 6.2	[1] 6.0	[1] 7.0	[1] 7.1	[1] 5.0	[1] 5.3	[1] 5.2	[1] 5.3

[1] Initial moisture content of soil column.

The surface inch or two usually has a slightly higher moisture content than the material below. This is probably due to the flooding of cavities at or near moisture saturation, which do not drain later under capillary tension. It is for the same reason that soils that have been flooded by irrigation often have a higher moisture content near the surface than soils that have been watered by a slowsteady rain. In a few of these samples, and presumably in all of Shaw's, water stood upon the surface at some time during wetting.

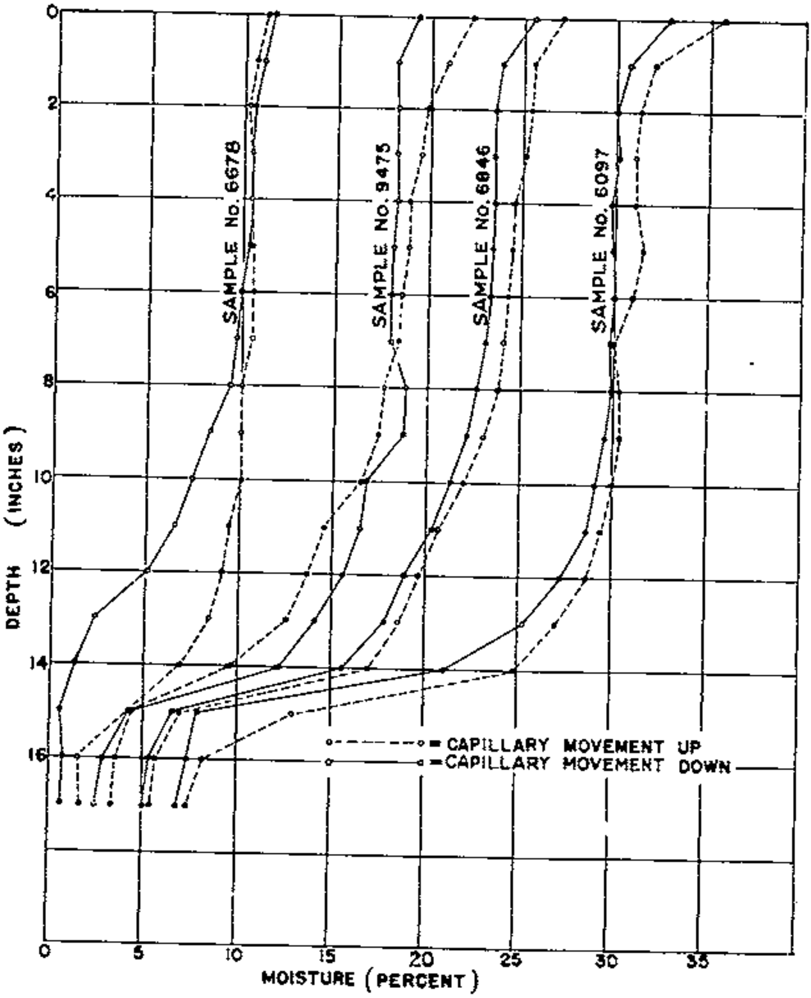

FIGURE 5.—The moisture at normal moisture capacity for four soil layers.

In these experiments the soil columns were not allowed to stand long enough for capillary movement of water to cease. After standing 3 or 4 days the line of color change, which marked the position of the capillary moisture front, did not move more than 2 or 3 mm per day. In some sandy soils the line of color change became indistinct after a few days and appeared to move forward more slowly than it did in the finer textured soils. Alway and McDole (*1*), working with similar soil tubes moistened at one end, found that at the end of 5 days "equilibrium had been practically attained in the silt loams, but in the coarser textured soils this was far from true." Shaw (*28*) found that water continued to move downward in a soil column throughout the 123 days it was allowed to stand. In this investigation one soil column of the surface layer of the Colby, allowed to stand for 345 days, had a moisture content of 24.6 percent at the upper end and 22.1 percent at the lower end, which had been initially dry. The normal moisture capacity of this sample was 29.9 percent. This soil sample was much nearer moisture equilibrium than were those of Shreve and Turnage (*29*) which, at lower moisture contents, were exposed for 2 years to much greater temperature variations.

The moisture content of the soil at the dry end of the column always slightly exceeded the initial moisture content even when the capillary front was several inches from the dry end of the tube. This water movement took place, quite certainly, in the vapor phase. It was to avoid excessive water-vapor movement that the soil columns were sampled after standing only 7 days. In determinations of the field capacity, samples usually are taken from 1 to 5 days after a rain or irrigation. Since no attempt was made to add identical quantities of water to each pair of soil tubes, the moisture tapers usually occurred at different depths. The taper ends abruptly at the line of color change, an abruptness not well shown by the data, because the color change occurs at varying positions within the 1-inch sample cores. The upward movement of capillary water against the earth's gravitational field was slower and the moisture content of the wetted portion of the soil column was greater than when the water moved downward. In sandy layers the differences in water content in the two cases usually were large.

In order to secure a numerical value for the normal moisture capacity, the average moisture content of the nearly uniformly wetted portion of the soil column was taken. In obtaining this average, the moisture value for the first inch of soil, usually the wettest, was rejected. The moisture value for the second inch was also omitted if it exceeded that of any subsequent section. The data of all subsequent 1-inch sections were included until one was reached whose moisture content was less than 90 percent of the average of the preceding sections. For example, the normal moisture capacity of sample 8069, table 3, is the average moisture content of the soil column from the second to the twelfth inch inclusive. This most uniformly wetted portion of the soil column was usually between 8 and 12 inches long. It might have been advantageous to use soil columns longer than 18 inches, but longer ones could not have been packed with the rotary compactor available. Whether the diameter of the tubes had an effect upon the moisture uniformity or moisture content of the soil column was not investigated.

The normal moisture capacity, determined as outlined above, together with other physical data, are presented in table 4. The data on specific gravity and moisture equivalent were taken from the work of Middleton, Slater, and Byers (*23*, *24*). The samples upon which the specific gravities were determined are not the same as those used in the other determinations, although both sets of samples were taken from approximately the same locations. This may cause some error in the computed relative volumes of air, water, and soil material given in the last three columns of the table.

TABLE 4.—*The normal moisture capacity and related data of the soils from the erosion experiment stations*

Sample no.	Moisture with upward capillary movement	Normal moisture capacity	Ratio of normal moisture capacity to moisture equivalent	Laboratory volume weight	Specific gravity	Volume of—		
						Soil material	Water	Air
	Percent	*Percent*		*G/cc*		*Percent*	*Percent*	*Percent*
COLBY SILT LOAM, HAYS, KANS.								
6842	29.9	28.2	1.03	1.21	2.64	45.8	34.1	20.1
6843	26.7	26.1	1.04	1.21	2.68	45.1	31.6	23.3
6844	25.2	26.4	1.01	1.27	2.69	47.2	30.9	21.9
6845	23.2	22.8	.97	1.25	2.68	46.0	28.5	24.9
6846	24.3	23.0	.93	1.20	2.69	48.0	29.7	22.3
6847	21.7	21.1	.89	1.28	2.69	47.6	27.0	25.4
HOUSTON BLACK CLAY, TEMPLE, TEX								
6996	30.5	29.5	0.97	1.27	2.64	48.1	37.5	14.4
6997	30.1	29.6	1.07	1.23	2.67	46.1	36.4	17.5
6998	26.0	26.0	1.07	1.29	2.60	48.0	33.5	18.5
6999	21.9	20.7	1.00	1.32	2.71	48.7	27.3	24.0
MARSHALL SILT LOAM, CLARINDA, IOWA								
B171	29.8	28.4	0.94	1.19	2.64	45.1	33.8	21.1
B172	32.1	30.4	.95	1.20	2.67	44.9	36.4	19.0
SHELBY SILT LOAM, BETHANY, MO.								
6797	25.4	24.7	1.01	1.27	2.62	48.5	31.4	20.1
6798	37.1	33.9	.97	1.23	2.66	46.2	41.7	12.1
6799	33.5	32.9	.96	1.22	2.70	45.2	40.1	14.7
6800	30.9	29.0	1.07	1.32	2.65	49.8	38.3	11.9
6801	24.2	23.9	1.01	1.38	2.72	50.7	33.0	16.3
6802	23.2	22.9	1.00	1.41	2.71	52.0	32.3	15.7
6802A	16.3	15.2	.91	1.48	(1)			
6802B	22.7	22.8	.97	1.36	2.71	50.2	31.0	18.8
CLINTON SILT LOAM, LA CROSSE, WIS.								
10362	22.1	22.0	0.92	1.23	2.64	46.6	27.1	26.3
10363	21.8	20.6	.88	1.26	2.70	46.7	26.0	27.3
10364	22.1	22.1	.89	1.25	2.71	46.1	27.6	26.3
10365	21.5	19.8	.88	1.30	2.70	48.1	25.7	26.2
10366	16.7	16.2	1.17	1.41	2.81	50.2	22.8	27.0
PALOUSE SILT LOAM, PULLMAN, WASH.								
8069	24.8	23.2	0.92	1.28	2.71	47.2	29.7	25.1
8070	27.2	25.5	.92	1.28	2.73	46.9	32.6	20.5
8071	27.4	26.4	.90	1.27	2.73	46.5	33.5	20.0
8072	21.5	22.8	.89	1.33	2.73	48.7	30.3	21.0
8073	23.5	23.0	.92	1.32	2.73	48.4	31.0	20.6
VERNON FINE SANDY LOAM, GUTHRIE, OKLA.								
6718	18.4	13.2	1.38	1.42	2.63	54.0	18.7	27.3
6719	16.6	11.9	1.31	1.39	2.66	52.3	16.5	31.2
6720	21.1	18.6	1.05	1.26	2.69	46.8	23.4	29.8
6721	21.6	20.7	1.13	1.40	2.69	52.0	26.8	21.2
MUSKINGUM SILT LOAM, ZANESVILLE, OHIO								
B407	23.0	23.1	0.91	1.26	2.66	47.4	29.1	23.5
B408	22.4	21.5	.82	1.31	2.70	48.5	26.2	23.3
B409	19.8	19.3	.92	1.40	2.68	52.2	27.0	20.8
B410	15.8	16.7	.86	1.48	2.75	53.2	24.7	22.1
B411	16.3	14.2	.72	1.56	2.78	56.1	22.2	21.7

[1] Not determined.

TABLE 4.—*The normal moisture capacity and related data of the soils from the erosion experiment stations*—Continued

KIRVIN FINE SANDY LOAM, TYLER, TEX.

Sample no.	Moisture with upward capillary movement	Normal moisture capacity	Ratio of normal moisture capacity to moisture equivalent	Laboratory volume weight	Specific gravity	Volume of—		
						Soil material	Water	Air
	Percent	*Percent*		*G/cc*		*Percent*	*Percent*	*Percent*
6678	10.2	10.1	1.28	1.53	2.69	56.9	16.5	27.6
6679	34.3	33.0	1.08	1.12	2.81	39.9	37.0	23.1
6680	29.8	28.5	1.00	1.18	2.81	42.0	33.6	24.4
6681	21.0	18.7	.88	1.31	(1)			
6682	19.2	13.2	1.97	1.34	(1)			

NACOGDOCHES FINE SANDY LOAM, TYLER, TEX.

Sample no.	Moisture with upward capillary movement	Normal moisture capacity	Ratio of normal moisture capacity to moisture equivalent	Laboratory volume weight	Specific gravity	Soil material	Water	Air
9475	18.7	18.0	1.24	1.36	2.86	47.6	24.5	27.9
9476	29.5	26.0	1.33	1.20	2.97	40.4	31.2	28.4
9477	27.9	26.9	1.07	1.12	2.86	39.2	31.5	29.3
9478	18.6	18.3	.98	1.23	(1)			
9479	23.3	20.8	.92	1.17	2.99	39.1	24.3	36.6

CECIL SANDY CLAY LOAM, STATESVILLE, N. C.

Sample no.	Moisture with upward capillary movement	Normal moisture capacity	Ratio of normal moisture capacity to moisture equivalent	Laboratory volume weight	Specific gravity	Soil material	Water	Air
6977	21.5	23.0	1.15	1.28	2.65	48.3	29.4	22.[illegible]
6978	26.5	24.7	.93	1.25	2.77	45.1	30.9	24.0
6979	26.0	25.6	.89	1.24	2.78	44.6	31.7	23.7

Scatter diagrams of the volume of soil material, water, and air plotted in turn against the sand, silt, and clay content revealed few single correlations. There is no significant correlation between the air volume and the silt or clay content. As would be anticipated, the relative volume of the soil material decreased with increasing clay content. The correlation coefficient was −0.63. However, there is no significant correlation between the volume of soil material and the sand or silt content. The largest relative volume of water occurs in clay soils, the correlation being 0.79. There is no significant relationship between the percentage of water by volume and the percentage of silt, but the correlation between water volume and sand content is −0.56. The Shelby profile has a very low air volume at normal moisture capacity. The residuals of table 7 indicate that the normal moisture capacities of the Shelby profile layers are higher than should be expected in soil samples of these textures.

The field volume weights published elsewhere (*24*) range from 1.03 to 1.91, whereas the laboratory volume weights of the samples upon which normal moisture capacities were determined range from 1.12 to 1.56. The single coefficient of correlation between the laboratory volume weight and the clay content is −0.71, indicating that there is in general an increase in void space in heavy textured soils. However, for the field volume weight the same coefficient is only −0.37, showing that the clay content is not the controlling factor in the apparent densities of soils under natural conditions of field packing. The laboratory volume weights on the average are 16 percent lower than the field volume weights, but the ratios between them are quite variable. There is a much closer agreement between the volume weights at moisture equivalent (from unpublished data of Middleton) and the laboratory volume weights than there is between either of these values and the field volume weights. The field volume weights were determined upon the entire soil material in place, but the other determinations were made upon the soil material which passed a 2-mm sieve. In most of the samples there was little or no material larger than that limit.

RELATION OF NORMAL MOISTURE CAPACITY TO MOISTURE EQUIVALENT AND TO FIELD CAPACITY

The relation of normal moisture capacity to other soil-moisture constants will be discussed in a subsequent section. However, it is desirable to present here some relationships between normal moisture capacity, moisture equivalent, and field capacity. The field capacity, which is the moisture content of a soil determined usually from 1 to 5 days after a rain or an application of irrigation water, is now of interest in subhumid areas in connection with soil-erosion problems. Nearly all the published data on field capacity were obtained in subhumid regions where there is usually a dry layer below the wetted portion of the soil. In these instances the moisture conditions are comparable to those required for the determinations of normal moisture capacity.

Israelsen (*17*) states: "It is highly desirable to establish if possible a relation between some of the more generally used soil constants and the maximum field capacity of the soil." He packed tubes with soil materials, saturated them with water, and then allowed them to drain for 24 to 46 hours. For 12 soils so treated the ratio between moisture content and field capacity ranged from 1.32 to 2.30. This high ratio is due to differences in structure and in capillary tensions between the soils in the field and in the laboratory. The tensions that existed in the soil tubes are comparable to those which exist in the field when the water table is near the surface.

Mathews (*21*) found that for certain soils of the Great Plains the field capacity is slightly less than the moisture equivalent. Burr and Russel (*9*) give the field capacity and moisture equivalent of 25 samples from texturally uniform silt loam soil profiles from central Nebraska. The average f. c./m. e. ratio computed from their data is 0.91, with an average deviation of only 0.5 percent. Veihmeyer and Hendrickson (*33*) determined the same ratio, which they termed the "relative wetness" for 19 California soils. The mean value was 1.06, with a mean deviation of 8 percent. The relative wetness was greatest for the sandy soils. Work and Lewis (*35*) obtained a mean value of the f. c./m. e. ratio of 0.82 for a soil so fine in texture that moisture-equivalent determinations were difficult to make. Harding (*15*) found a decrease for the ratio from about 1.5 for sandy soils with a moisture equivalent of 5 percent to about 0.75 for soils with a moisture equivalent of 30 percent. In Harding's experiments the moisture-equivalent determinations were not made upon the samples used to determine the field capacities.

Some of the variations in these ratios may be due to the field-moisture sampling. If the samples were taken while capillary movement was still relatively rapid the moisture determinations would be too high. Sandy soils permit the most rapid movement of gravitational water but apparently the slowest movement of capillary water except at low capillary tensions.

Field-capacity determinations are not available for the soils used in these investigations so that a direct comparison of moisture equivalent and field capacity is not possible. In table 4 are given the ratios of normal moisture capacity to moisture equivalent. Figure 6 is a scatter diagram of the ratio n. m. c./m. e. plotted against the moisture equivalent, the latter being used as an index of texture. The figure shows no significant effect of texture upon the n. m. c./m. e. ratio except that it is high in sandy soils. The average value of the ratio is 1.02, with an average deviation of 12 percent. By omitting eight sandy layers from the average the ratio becomes 0.96, with an average deviation of 8 percent.

Although directly comparable data of normal moisture capacity and field capacity are lacking, the similarity of values of n. m. c./m. e. and f. c./m. e. leads one to believe that the normal moisture capacity, as determined in this investigation, is a better measure of field capacity than is the moisture equivalent. Obviously it is a better index than moisture equivalent in sandy soils. The structure and packing may not be the same in the soil columns as in the field, but the capillary tensions and boundary conditions are essentially the same when the field capacity is determined with the sampled layer in contact with a dry one beneath.

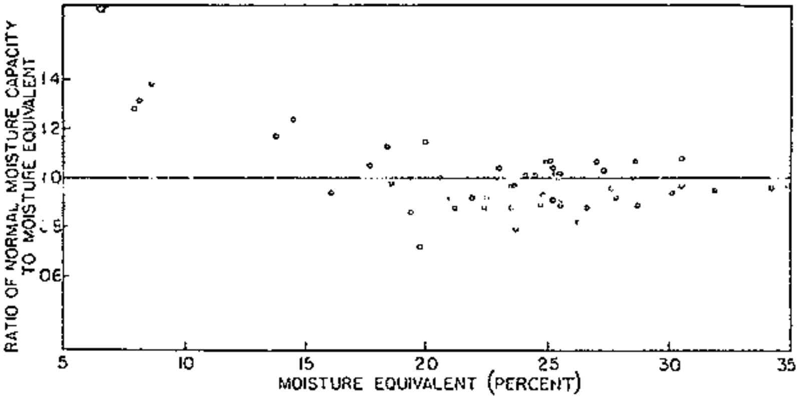

FIGURE 6.—Scatter diagram showing the relation of the ratio of the normal moisture capacity to moisture equivalent for soils whose textures are represented by the moisture equivalent.

Table 3 and figure 5 illustrate the familiar but remarkable soil-moisture phenomenon upon which the practice of fallowing is based. When water enters the soil surface it moves down into the dry soil as rapidly as the pore-size distribution will permit. When the gravitational water is exhausted and the water meniscuses at the soil surface develop tensions of the order of one-half to one atmosphere, the downward movement of capillary water becomes very slow. After a few inches of the surface layer dry, the upward capillary movement of water becomes very slow, and water remains in the soil available for plant use.

THE STICKY POINT

Atterberg (*4*) employed the sticky point, or Klebegrenze, as a soil-moisture constant to separate the plastic consistence of soils into two parts constituting the sticky and nonsticky ranges. Hardy (*16*) regarded the sticky point as the condition of maximum plasticity and accepted the onset of stickiness as marking the saturation stage of the colloid component of clay and soils. Atterberg defined the sticky point as the moisture content of a drying clay paste when it just fails to stick to a nickel spatula drawn across the surface. Hardy's criterion was the failure of the drying soil mass to adhere to the fingers.

Russel and Wehr (*26*), approaching the sticky point from the dry side, chose as the end point the stage at which a nickel spatula, pressed firmly against a freshly exposed soil surface and drawn quickly across it, distinctly did not scour. By quickly they meant, apparently, speeds approaching that ordinarily attained by tillage instruments. With decreasing spatula speeds, the samples required higher moisture contents to cause sticking. They called the limiting condition at a very slow spatula speed the static scouring point. For a sample of Houston black clay from Texas the moisture content at the higher scouring point was 39.7 percent above the lower one.

Keen and Coutts (*19*) employed a small dough-mixing machine for sticky-point determinations. A perceptible clean-up of the sides and base of the machine was observed when the wet soil mass dried to the sticky point. The machine was soon rejected because it required too large soil samples and was too inconvenient to clean. The procedure Keen and Coutts finally employed was to mix a wetted 10-g soil sample on a glass plate with a spatula, and then to knead the sample by hand until the soil no longer stuck to the hands or to a spatula drawn through it. Charlton (*11*), who used the same technique, emphasized the necessity of approaching the end point from the wet side only. Bodman and Perry (*6*) chose as the end point the condition when the kneaded soil, pressed against the thumb, no longer stuck to it. They attempted to apply the same pressure at each test. Prescott and Poole (*25*) state that the Keen and Coutts spatula test is the only satisfactory criterion for the heaviest clays. For less plastic soils they found "the best guide is the ability to handle the (soil) blocks with gentle squeezing or pressing on the palm of the hand with little or no adherence to the skin." They used another technique applicable to sandy soils which are nonplastic and are commonly regarded as nonsticky.

Whatever sticky-point technique was used, most operators report that they were able to obtain satisfactory replication of their own results without difficulty, and, in some cases, that others instructed by them in the technique were able to secure satisfactory checks. However, in a cooperative project undertaken by commission I of the International Society of Soil Science and reported by Keen (*18*), it was found that workers employing the technique described by Keen and Coutts but not instructed personally by them obtained widely varying values for the sticky points of subsamples of the same soils. Keen recommended that attempts be made to modify the technique to a form that will permit its use as an accurate routine method.

In preliminary tests of the sticky point of the soils of the erosion experiment stations, no sharply marked end point was found with any of the published procedures. Often it was difficult to decide from the appearance of the hand or the spatula whether the soil should be classed as above, below, or at the sticky point. Some lateritic clays left red stains on clean dry skin surfaces at moisture contents below the lower plastic limit of Atterberg. In most instances, as the moisture content of the kneaded soil mass was increased, the soil film left on the hand gradually increased in thickness until finally the adhesion to the hand was sufficient for the rupture to take place well within the soil mass. When the sample was squeezed between the thumb and fingers or pressed against the back of the hand or against a glass plate, it was necessary to decide whether one should employ uniform pressure, as Bodman and Perry had done, or uniform deformation; and in either case, how great the pressure or deformation should be. In some procedures it was necessary to decide whether, after kneading the sample, the hand should be cleaned and dried before making the test. Some soil pastes at certain moisture contents would stick to the hand or spatula but not to both. In some instances the soil would stick to a stainless-steel spatula which cut it, but not to the flat side of the spatula drawn over the soil surface. It was found that raising the cutting speed always lowered the point of stickiness. By varying the procedure the sticky point of some soils could be shifted over nearly the whole of the Atterberg plastic range. The plastic characteristics of some lateritic soils were so different from those of soils with high silica-sesquioxide ratios that the criteria of stickiness that gave good reproducibility with the one class often were quite unsatisfactory for the other class.

METHODS

The only hope of obtaining a satisfactory technique appeared to lie in some form of mechanization. The first device tried was a smooth steel rotating disk with a sharpened edge connected through reducing gears to a variable-speed motor. The soil paste could be held against the face or edge of the disk, which could be rotated at any desired speed. The action was not greatly different from that of the spatula except that the movement was continuous and the speed was known and uniform.

This apparatus did not prove to be so satisfactory as a simple device similar to the one illustrated in figure 7. It consisted of a polished steel roller horizontally held in plain brass bearings. The soil material, placed on the movable plate, was fed under the roller. The clearance between plate and roller was about 4 mm. The roller, about 20 cm long and exactly 5 cm in circumference, had a short crank attached to it. The roller was made of drill-rod steel, but, no doubt, stainless steel would have been preferable. The bearings were separated far enough for a brass plate about 10 cm wide and 15 cm long to slide between them. The entire apparatus was made in about 3 hours from scrap materials picked up in the laboratory shop.

The procedure employed with the roller was as follows: A 15- to 20-g soil sample, which had passed through a sieve with 2-mm round holes, was moistened with distilled water and thoroughly puddled by kneading with the hands or, more often, by mixing with a spatula, upon the movable plate of the tester. The sample upon the plate was fed against the roller, which was rotated in the direction that forced the soil paste underneath it. The desired end point was attained when the soil barely failed to stick to the roller at a shearing speed of 5 cm per second. A moisture sample was then taken.

RESULTS

Table 5 presents the results of preliminary sticky-point tests made by several methods upon six erosion station samples and the Nipe subsoil, a ferruginous laterite from Cuba. It was from these tests and from the experience gained in securing these data that the selection of a sticky-point procedure for subsequent work was made. The tests were made by use of the roller, the rotating disk, the spatula, by adhesion to a glass plate, and by adhesion to the hands, the latter by two criteria. The lower value was obtained by taking the point at which the soil began to stick in appreciable quantity to the dry knuckle or back of the finger with a uniform deformation somewhat less than that employed in the glass-plate test. In the other finger test, which was approached from only the dry side, the end point was reached when the plastic soil mass first began to stick in considerable quantity to the fingers used in kneading it. The hands were not cleaned and dried in this test. In the glass-plate test, a 5- or 6-g soil sample was molded into a cube, and then one corner was pressed against a clean dry glass plate until the diagonal of the cube was shortened about one-third its initial length. The end point was reached when approximately 5 to 10 mg of soil adhered to the plate.

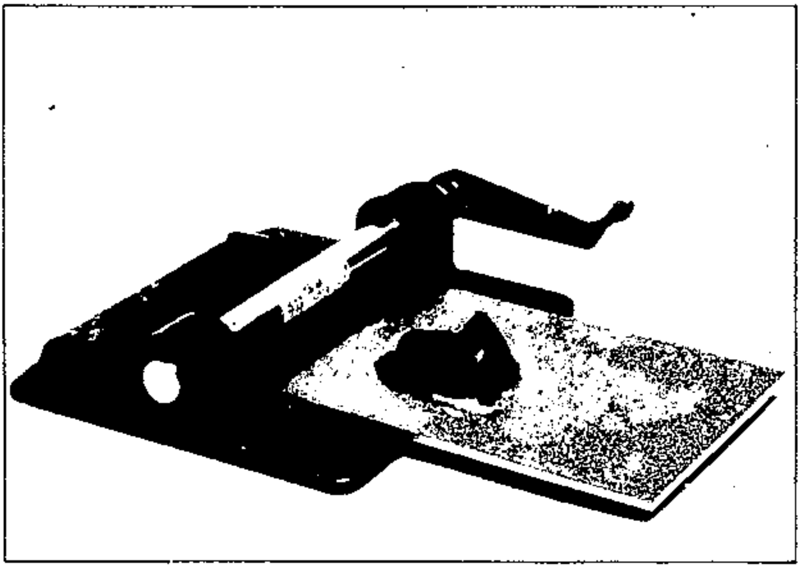

FIGURE 7.—Sticky-point tester.

In the spatula test, an attempt was made to draw a 4-inch stainless-steel spatula at a constant speed estimated to be about 5 cm per second.

TABLE 5.—*Sticky points of soils by different procedures*

Soil sample no.	Finger test lower value	V[1]	Finger test higher value	V[1]	Glass plate	V[1]	Spatula	V[1]	Rotating disk	V[1]	Roller	V[1]	Average	
													Sticky points	V[1]
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
B172	36.2	1.0	39.5	1.0	38.9	0.9	36.8	1.3	36.8	0.5	38.0	0.3	37.7	0.9
10362	28.2	.9	31.3	.8	27.9	3.0	(2)	----	(2)	----	(2)	----	29.1	1.0
10365	27.8	1.2	30.9	1.3	30.5	.8	29.2	.7	29.7	.6	31.1	.9	29.9	.9
6720	21.3	2.2	23.5	1.7	21.7	1.4	21.7	1.5	22.7	1.5	21.2	1.5	22.0	1.6
6007	33.0	1.2	40.1	1.1	32.4	1.0	27.8	1.8	28.4	1.2	28.8	.8	31.8	1.2
6978	34.8	1.6	40.2	1.2	38.1	1.2	35.2	.9	37.1	1.4	35.5	.9	36.8	1.2
Nipe clay	35.3	1.0	38.4	1.4	36.1	1.0	36.1	1.1	36.2	1.2	35.6	1.6	36.3	1.4
Average[3]	31.4	1.4	35.4	1.3	33.0	1.1	31.1	1.2	31.8	1.1	31.7	1.0	--------	----

[1] V = coefficient of variability.

[2] Not sticky.

[3] No. 10362 omitted.

Two determinations were made by each procedure on the same day, but the duplicate tests were not made consecutively. This was done in order to detect possible shifts in judgment of the end point. A new sample was taken for each test from a larger stock sample which previously had been prepared by moistening and thoroughly kneading. The values given in table 5 are the averages of six determinations, and it is upon the sets of six replicates that the coefficients of variability were computed.

The six procedures may be divided into two groups. The glass-plate and the finger tests are based upon the adhesion of the soil to a surface against which it is pressed to produce a small deformation. These may be regarded approximately as static tests and for brevity will be designated as such. The other three tests, which are dynamic, are based upon adhesion of soil to a smooth metal surface at a definite rate of shear. These may be regarded more appropriately, perhaps, as scouring points.

All methods gave about the same results for a few soils, such as the Nipe. It was necessary to knead this soil for 20 minutes or more before sufficient deflocculation was obtained to secure the values given in table 5. All samples of the Houston profile, of which sample 6097 is an example, gave higher sticky points by the static methods than by the dynamic ones. Sample 10362, from the surface layer of the Clinton, would not adhere to metal. It did not possess a true rolling-out limit, or Ausrollgrenze, and consequently would be rated as nonplastic and nonsticky in the Atterberg soil-consistence classification.

Although the number of replications was not sufficient to yield highly significant variability coefficients, the average value of the coefficient for none of the procedures is excessively large. This may be due as much to the fortunate circumstance that the subjective criteria of some of the end points did not shift during the few days required to complete the determinations as to the care in making them. In making these determinations, the end points were repeatedly checked and, wherever possible, approached from both the wet side and the dry.

In the selection of a standard sticky-point procedure the higher value finger test should certainly be rejected, not only because it is slow, inconvenient, and messy but also because it yields values clearly above the minimum point of stickiness. The test was included here to indicate the maximum value any operator reasonably can be expected to obtain by a procedure involving adhesion of soil material to the hand. In the writer's experience, the glass-plate test was the most satisfactory of the static ones used and has the advantage of employing a small sample. The brief description given of the procedure for the test is expressed in quantitative terms which are believed to be sufficiently definite for other workers to follow. The method, however, yields sticky points for soils that are nonplastic according to the Atterberg classification.

For the soils reported in table 5 all procedures based upon shear by metals gave closely comparable results with small variability coefficients. Of these procedures the roller method was by far the most satisfactory and was the one adopted for determining the sticky points of all the soils under examination. By varying the roller speed one can readily learn whether the moisture content of the sample is above or below the sticky point, and by the same means the sticky point can repeatedly and continuously be checked. During the test the soil is being mixed constantly, and fresh surfaces are being exposed to the roller. At the end point a shearing speed in excess of 5 cm per second causes the soil mass to wrap around and follow the roller, and at slower than standard shearing speeds the roller clears. With most soils there is a definite clean-up of the roller at a definite speed, but in some cases the change in roller appearance is not so easily interpreted, and this may give rise to differences in the results of different operators. This situation usually occurs with coarse sandy clays, with some lateritic soils, or with soils on the border line between sticky and nonsticky consistence. It does not occur so often with the roller as with the spatula test. When a spatula is drawn through a wet sandy soil a thin film of clay often is left upon the blade. This is not evidence of stickiness of the sample as a whole and seldom occurs in the roller test.

Subsequent to the completion of the sticky-point determinations reported in this investigation, G. H. Cashen of the Rothamsted Experimental Station kindly demonstrated to the writer his technique for sticky points. He gently squeezed a kneaded mass of about 30 to 40 g of plastic soil in the dry clean palm of the hand. The criterion of stickiness appeared to be more the feel of a slight pull of the soil upon the skin as the hand was opened than upon the adhesion of soil material to the palm.

A few erosion station samples have since been checked by this method, as nearly as it could be recalled some 3 months after the brief demonstration upon one soil. The end point chosen was that at which the squeezed soil mass gave a slight pull to the dry clean palm as the hand was opened. The exact squeeze and pull cannot be quantitatively expressed or accurately described, but the squeeze was just sufficient to give, in the operator's judgment, a close contact of the soil mass to the skin, and the pull was a little greater than the minimum perceptible one. No consideration was given to the quantity of soil material adhering to the hand. This may be the procedure of Prescott and Poole (*25*) in which the adherence was slightly greater than their "little or no adherence to the skin", and was judged by feeling only.

From the few determinations made by this procedure, it appeared to be as reproducible as any of the static tests, and the end points appeared to be more definite than with any other static method except the glass-plate test. The results usually were 1 or 2 percent higher than those obtained by the roller method, but in the case of the Houston clay the values ran from 4 to 8 percent higher. In common with other static tests, end points could be obtained for some soils that could not be made to follow the roller.

Table 7 gives the sticky-point determinations of the profile samples of the erosion station soils by the roller test at shearing speeds of both 5 and 10 cm per second. The relation of these data to other physical and chemical soil properties will be discussed in a subsequent section. The data obtained at the slower shearing speed are to be regarded as the sticky point. The data at 10-cm-per-second shearing speed are presented only for comparison with the standard values. The determinations are the averages of three pairs of duplicates.

The duplicates were not made consecutively. Any result regarded as having an excessive deviation from the average was rejected, and the determination was repeated. No fixed standard for this deviation was maintained because the end points, for instance, of the Colby were much more definite than those of the Clinton and Muskingum. Texture considered, the least plastic soils had the highest moisture contents at the sticky point and the largest deviation of replicates. Fourteen of the samples could not be made to stick to the roller at definite moisture contents within the plastic range.

In this work the Atterberg principle that the sticky point and the lower plastic limit are consistence forms of plastic soils only was followed. Neither Prescott and Poole (*25*) nor, apparently, Keen and Coutts (*19*) placed this limitation upon their determinations. The latter reported sticky points for soils with less than 2 percent of clay, and for sandy soils the former used a special technique based upon water saturation of the sample and in no way involving sample deformation or soil plasticity. In table 7 are presented lower plastic limit data for four soils for which no sticky points are given. These four soils are about at the border between plastic and nonplastic consistence. The lower plastic limit tests were sufficiently definite to rate the soils as barely plastic. With persistence and care the soils could be made to follow the roller, but the moisture contents were so high and so variable in replicates that the soils on this test were rated as nonsticky and nonplastic. Upon the addition of sodium hydroxide these four soils became plastic.

Some silty soils, low in clay, may be made to follow the roller at high moisture contents and high roller speeds. Sticky points at moisture contents considerably above the minimum water of saturation were regarded as false end points. Soils that are only slightly plastic show large variations in replicate determinations of the sticky point. As compared with other moisture constants, such as the moisture equivalent and minimum water of saturation, the sticky points are lowest in the most plastic soils.

Stiff pastes of most of the lateritic soils examined lack the cohesiveness of pastes made from other soils and tend to break up into lumps when fed against the roller or when a spatula is drawn through them or over their surfaces. They are nonsticky at much higher clay contents than are the soils of the other groups. From the high clay content one would expect samples 9477 and 9479 of the Nacogdoches profile to be highly plastic. They do become highly plastic when treated with small quantities of sodium hydroxide.

Table 6 illustrates the effects upon the sticky point of the addition of sodium hydroxide to a few soil samples. Dilute solutions of sodium hydroxide were added to the soil material until pH 7.0 or 8.1 was reached or slightly exceeded. The kneaded soil mass was kept overnight in a closed container. The next day the addition of more sodium hydroxide was required to bring the pH values to 7.0 or 8.1 again. The sticky point and lower plastic limit were then determined. If the duplicates checked well in these determinations no further replication was made.

TABLE 6.—*Sticky point and lower plastic limit of soils treated with sodium hydroxide*

Sample no.	No sodium hydroxide		Sodium hydroxide to pH 7.0		Sodium hydroxide to pH 8.1		Exchangeable bases[1]	Exchange-base capacity[1]	pH[1]
	Sticky point	Lower plastic limit	Sticky point	Lower plastic limit	Sticky point	Lower plastic limit			
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Milliequivalent*[2]	*Milliequivalent*[2]	
9476	28.0	20.1	25.0	19.3	23.2	18.2	16.8	19.6	4.4
9477	(3)	(3)	30.4	21.9	23.7	18.8	12.7	20.6	4.6
9478	31.5	20.0	28.9	19.9	26.0	16.6	9.7	20.6	5.0
9479	(3)	(3)	28.2	19.8	21.7	16.9	14.5	19.1	5.1
B407	(3)	(3)	(3)	21.7	25.7	19.3	23.3	35.0	4.7
B408	37.0	23.1	30.0	19.6	25.4	18.8	26.1	33.5	4.8
B409	(3)	(3)	34.9	21.4	29.7	20.7	15.8	21.3	4.8
B410	(3)	(3)	22.4	20.1	22.7	19.4	17.0	19.0	4.8
B171	36.1	22.6	32.8	20.8	31.2	19.3	60.1	65.1	5.5
B172	38.1	22.4	35.2	21.3	34.9	19.9	62.9	65.8	5.6
6797	31.3	19.6	(4)	(4)	20.5	16.6	61.9	62.5	5.4
6798	34.2	19.8	(4)	(4)	33.4	18.7	69.3	61.4	5.6
6799	33.8	17.6	(4)	(4)	33.7	18.1	70.7	60.6	7.0

[1] Data taken from Slater and Byers (*30*).
[2] Per 100 g of colloid.
[3] None.
[4] Not determined.

In the last three columns of table 6 are given the exchangeable base content, exchange-base capacity of the extracted colloids, and pH value of the untreated soils. The base-exchange capacities of the Nacogdoches and Muskingum layers are so low that only about 3 milliequivalents of sodium per 100 g of dry soil were required to bring the samples up to neutrality. The colloids of the other soils were so nearly saturated that they, too, required the addition of only small quantities of sodium. The hydrogen-ion concentrations were determined colorimetrically, employing bromthymol blue and cresol red. The end-point colors were checked against buffer solutions. The sticky points were determined by the roller method with shearing speeds of 5 cm per second, and the lower plastic limits were determined by the procedure given in a later section of this bulletin.

The nonplastic Muskingum profile samples are finer texturally than some layers of the Shelby, which are quite plastic. The only untreated sample of the Muskingum for which a sticky point could be obtained was B408, and even this value is so greatly in excess of the minimum water of saturation as to cause doubt whether the sample is really plastic. Upon the addition of sodium ions all layers became plastic. Samples 9477 and 9479 of the Nacogdoches profile are sandy clays without definite sticky points when tested by the roller. Upon the addition of sodium ions they became highly plastic. The sodium hydroxide treatment increased only slightly the plasticity of the subsoils of the Marshall and Shelby, as is shown by the lowering of the sticky points and lower plastic limits. When sodium hydroxide was added to samples from the lower horizons of the calcareous Colby and Houston, the sticky point was raised, and in sample 6847 a definite sticky point could no longer be obtained. After the removal of organic matter with hydrogen peroxide treatment the sticky point of sample B171 was lowered from 36.1 to 29.6, and the lower plastic limit was reduced from 22.6 to 17.2. There was a slight but scarcely significant decrease in the minimum water of saturation. The lowering of the sticky point and lower plastic limit of soils by hydrogen peroxide or sodium hydroxide treatment may be due in part to the increased dispersion of the clay aggregates.

Charlton (*11*) reported sticky-point determinations by the Keen and Coutts procedure for some East Indian soils whose bases had been replaced by hydrogen, calcium, or sodium. He found that hydrogen or calcium saturation raised the sticky point above that of the untreated soil, but that sodium saturation and hydrogen peroxide treatment lowered it. In the samples reported in table 6 the bases replaced by sodium were not washed out of the soil, so that the treatment is not comparable to that of Charlton. In this work the depression of the sticky point in the selected samples at pH 8.1 was considerably greater than the average depression obtained by Charlton for sodium-treated samples at pH 8.4. Anderson (*3*) found that the alteration in several physical properties of extracted soil colloids was least in colloids of low silica-sesquioxide ratio.

DISCUSSION

It seems evident that the various methods which have been employed to determine the sticky point of soils do not all measure the same soil property. If the term "sticky point" is to be applied to those tests which depend upon adhesion of the soil to surfaces against which it has been pressed, then perhaps the term "scouring point" should be used to designate adhesion of soil material sheared by polished metal surfaces. For some soils the two procedures may be made to yield essentially duplicate results, but for other soils the values may differ considerably. Furthermore the static tests yield sticky points for many soils which are not sticky according to dynamic tests. Whether both types of tests are to be retained will depend on the uses and value of the information which they furnish.

If the static tests are to be used there is need for standardization of the procedure. None so far found in the literature appear to be capable of quantitative description, or to have been described precisely enough to yield consistent results by different workers without personal demonstration. The least subjective of the methods that have been used appears to be the glass-plate test used in the preliminary work of this investigation. Apparently no successful attempts have been made to mechanize the static sticky-point procedure.

The dynamic methods of determining the sticky point appear to be simpler and to offer greater hope of standardization. The most important item is the shearing speed. It is believed that the roller device employed in this investigation offers a more satisfactory basis for a standardized procedure than any of the other methods now in use. The only specifications that appear to be of importance are the size and peripheral speed of the roller and possibly the clearance between the roller and the plate. At high shearing speeds it is difficult to observe small particles of soil adhering to the roller. High shearing speeds lower the sticky point and, in border-line cases, may yield sticky points for soils which cannot be made to follow the roller at the chosen shearing speed of 5 cm per second. Shearing speeds of 3 or 4 cm per second can also be used satisfactorily. These speeds yield slightly higher sticky points, which are more nearly in line with the values obtained by the writer when using static methods. However, the two types of procedures yield such widely varying results in some instances that, in fixing the shearing speed, no consideration need be given to the results by static methods.

Although nearly all soils may possess plastic properties to a slight degree, light-textured soils do not fall within the plastic-consistence classification of Atterberg. It seems possible that the dynamic sticky-point procedure may be so chosen that only those soils which fall within the Atterberg plastic range will be rated as sticky. The essential requirement is that soils which have lower plastic limits and no others shall also have sticky points. The data, which will be discussed later, show that there is a close relationship between the sticky point obtained by the roller method and the lower plastic limit. The unique relationships of these plastic-consistence constants appear to justify the adoption of such a mechanized dynamic procedure.

THE LOWER PLASTIC LIMIT

METHODS

All published procedures for the determination of the lower plastic limit are based on the Ausrollgrenze of Atterberg (*4*). They differ chiefly in the manner of rolling the sample and the end-point criteria. As one repeatedly rolls out a 2- to 3-g subsample of a kneaded plastic soil at a moisture content slightly below the sticky point upon a sheet of glazed paper or a glass plate, with the fingers (*4*), a finger (*26*), the palm of the hand (*2*), the side of the palm of the hand, or a stick (*6*), a moisture content of the drying paste finally is reached at which the soil filament begins to break into lengths of perhaps 1 to 3 cm. If the cross section of the soil filament does not appear homogeneous but shows a spiral line or laminations due to rolling, some operators consider the end point to be reached even though the broken pieces of filament may be rather long. Others, such as Russel and Wehr and the writer, interpret the term "Ausrollgrenze" literally and drive the end point down to the lowest value at which the soil may be made to roll out into a filament of 3 or 4 mm diameter and about 1 cm long.

At the rolling-out limit, the finest textured and most plastic soils are the stiffest. Some of them require a greater rolling pressure than conveniently can be exerted by the finger or hand. In this investigation the samples were rolled between the side of the palm and a smooth glass plate, a condition favorable, when necessary, to high rolling pressures. In the few cases encountered in which the soils were too stiff to roll, the technique of Russel and Wehr (*26*) was followed, in which the samples were struck with a hammer. At moisture contents above the end point the sample flattened out into a thin layer. Below the end point the sample shattered into small fragments. The end point was taken in the narrow slightly uncertain moisture zone dividing the two conditions described.

Coarse-textured soils cannot be made to roll out into filaments, but there is no sharp division between soils that have an Ausrollgrenze and those that do not. Neither is there general agreement among operators as to whether soils in the zone near the plastic-nonplastic boundary have a true rolling-out limit. Some sandy soils fairly high in well-decomposed organic matter, if skillfully handled and gently rolled, may be made to assume a cylindrical form at moisture contents at or above saturation. In fact they may show a glisten such as is observed in determinations of the minimum water of saturation. In this investigation soils were considered to have no Ausrollgrenze unless they could be rolled freely, showed typical filament breakage, and had moisture contents below the minimum water of saturation.

As in sticky-point determinations, the soils for which definite and reproducible plastic limits were most difficult to obtain were those near the border line between the plastic and nonplastic consistences. These soils gave high values which approached or occasionally slightly exceeded the moisture equivalent. Slightly plastic lateritic soils formed rough granular filaments instead of the usual smooth-surfaced structureless ones. Near the end point they broke into crumbs instead of the usual short cylindrical sections. Some also adhered to the hand or glass plate if sufficient pressure was applied. Upon the addition of sodium hydroxide, a deflocculent, these conditions disappeared, the soils rolled freely, and gave lower and definite end points. Table 6 indicates that sodium hydroxide lowered the lower plastic limit for all acid soils with low base-exchange capacities.

The writer has found in soils literature no attempt to mechanize the procedure. Although the easiest of all Atterberg consistence constants to define and to determine, it depends, as do the other Atterberg constants, upon the judgment of the operator. Each operator can usually duplicate his own results within 1 percent of moisture, but his results may differ widely from another operator's. In the writer's opinion the technique most likely to yield comparable results by different operators is the one in which the end point is driven to the lowest value which can be made to conform to the procedure description. The end point can be approached only from the wet side. The effect of temperature variations has not been investigated, but it is quite probable that considerable variation in the temperature of the glass plate will appreciably affect the end-point values.

RESULTS

The data obtained for the lower plastic limit of the erosion station soils are presented in table 7 and will be discussed in a later section. With a few doubtful exceptions the lower plastic limit lies between the centrifugal moisture and the other capillary soil-moisture constants given in the same table. It lies in an agriculturally important moisture range, apparently being the moisture constant nearest the permanent wilting percentage. Its values run so low in highly plastic clays and so high in barely plastic soils that it probably bears no definite relation to the moisture content of the soil at which plants permanently wilt. The lower plastic limit appears to bear no fixed relation to any of the other soil-moisture constants, not even to the sticky point, which is also a property of plastic soils.

For two horizons of the Muskingum and one each of the Clinton and Kirvin soils, lower plastic limits, but no sticky points, are given. This is also true of one sodium hydroxide-treated sample in table 6. These appear to be border-line cases in which it is uncertain whether the soils should be rated as plastic or nonplastic in the Atterberg classification. In these four instances the soils could be made to adhere slightly to the roller at higher speeds, but the moisture contents were so high and the results of replication so variable that these soils were rated as nonsticky. However, the lower plastic limits were sufficiently reproducible by the procedure employed to warrant, in the writer's opinion, the rating of these soils as plastic. The writer was unable to make a satisfactory modification of either procedure which would definitely give these soils either both constants or neither of them, as a perfect plastic consistence classification would seem to require. Procedures differing from those used in this work may accomplish this result, but if the discrepancy is found to be limited to boundary cases the procedures adopted in this investigation are not open to very serious criticism for that reason. It seems quite unlikely that any static sticky-point method may be made to agree so well with the lower plastic-limit tests as does the roller method.

MINIMUM WATER OF SATURATION

METHODS

The term "minimum water of saturation" is used in this bulletin to designate the lowest moisture content at which free water appears on the surface of a soil sample in closest packing. The procedures employed in the determinations were as follows:

A sample of soil material that had passed a sieve with 2-mm round holes was mixed with distilled water to form a coherent mass. A portion of about 4 g was worked between the thumb and index finger, with small deformations, into a cubical form whose edges were about 1.5 cm long. The object of the manipulation was to produce a particle orientation that would reduce the soil voids to as low a volume as could be obtained without compression. The desired end point was the lowest moisture content at which a glisten appeared upon the surface of the sample. After the end point was obtained, the sample was dried overnight at 105° C., and the moisture content was determined.

The end point was quite easily checked in sandy soils by deforming the sample slightly so as to increase the porosity. This treatment caused the free surface water to retreat into the interior of the sample and the surface glisten to disappear. Unlike sandy soils, the clays did not have a perceptible volume rigidity due to soil-grain arrangement, and movement of water from the surface did not take place in these soils when there was a slight change in shape of the molded sample. The end point was also much more difficult to observe than in the lighter nonplastic soils. Consequently the procedure was modified for clay soils. The wetted samples were worked into spherical shapes and then lightly tapped a few times upon a glass plate to produce a flattened area a half centimeter or more in diameter. The end point was the lowest moisture content at which there appeared a narrow glistening ring surrounding the flattened area. These soils could be manipulated at moisture contents above the sticky point by employing light pressures and producing only small deformations. When soil material stuck to the fingers there existed the possibility of particle-size fractionation which might affect the accuracy of the result.

The end point for each sample was approached from both the wet side and the dry, a procedure that could be repeated as often as desired. In adjusting the moisture content, water could be drained away from a sample too wet by touching one face to a dry glass plate. If the sample was too dry, a drop of water, added to the top, was distributed quickly by capillarity, if the texture was not too heavy.

Clay soils required thorough mixing after water was added to them. Many sandy soils cannot be molded into shape except at moisture contents considerably above the end point.

This moisture constant is open to the same serious objection as the Atterberg consistence constants, that the end point depends upon the judgment of the operator. In some instances it is impossible to determine with certainty, over quite a wide moisture range, at what point the soil surface begins or ceases to glisten. Perhaps the decision may be affected by lighting, eye fatigue, or acuteness of vision. Other objections are that the voids may not be filled completely with water and that the manipulation of clay soils may produce a volume greater than the minimum.

Notwithstanding the element of personal judgment entering into the tests, there are advantages which appear to warrant its retention if the results are found to be useful. It is a test which can be applied to all mineral soils except the very coarsest. It requires only a small sample, without pretreatment, and no equipment except that needed for drying and weighing. Replicates for nonplastic soils usually agree within less than 1 percent of moisture. For clays the replication is not quite so precise as for the sticky point. There is no assurance, of course, that the results obtained by different operators will agree within these limits.

The greatest difficulty in securing satisfactory duplicates occurred with lateritic clays. It was found that fewer erratic results were obtained if, starting with a soil too dry, tests were made at increasing moisture contents until the sample definitely was too wet, and then watching for the end point until the soil barely was too dry. A drop of water was then added for a final check.

RESULTS

The data on the minimum water of saturation obtained for the erosion station profile samples are presented in table 7 and further discussed in a later section. The determinations were made nonconsecutively at the same time as those of the sticky point and lower plastic limit. The values recorded are the averages of six determinations.

Scatter diagrams indicate that the minimum water of saturation more nearly parallels the clay content than any of the soil-moisture constants studied. Its average value is slightly lower than that for the sticky point but is above the values for the other moisture constants recorded in the table. For sandy soils the value should be lower than those which Prescott and Poole (*25*) obtained by a somewhat similar procedure for the sticky point because in this investigation the samples were worked into the condition in which the soil grains were most closely packed.

TABLE 7.—*Soil-moisture constants and related data of the soils from the erosion experiment stations*

Sample no.	Sand	Silt 2μ-50μ	Clay <2μ	Organic matter	Minimum water of saturation		Normal moisture capacity		Sticky point		Sticky point (10 cm per second)		Moisture equivalent		Lower plastic limit		Centrifugal moisture		Water-vapor absorption	
					Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
COLBY SILT LOAM, HAYS, KANS.																				
6842	18.0	49.0	30.2	2.8	30.6	0.1	28.2	1.2	33.0	3.0	31.7	2.9	27.3	0.6	19.0	1.1	10.7	0.3	9.6	0.8
6843	18.6	47.9	32.1	1.1	30.5	−.6	26.1	1.4	29.8	−.8	28.8	−.2	25.2	−.6	16.2	−2.4	11.1	.2	9.1	−.5
6844	13.7	55.1	30.3	.6	29.3	−1.0	24.3	.8	28.4	−2.2	26.8	−2.2	24.1	−1.1	17.5	−3.1	10.8	−.1	8.6	−.4
6845	13.8	57.3	28.6	.3	28.5	−.9	22.8	.3	28.2	−1.9	25.2	−2.3	23.6	−1.1	15.5	−2.9	10.6	−.4	8.7	.1
6846	10.8	60.1	29.0	.1	29.9	.2	23.0	.5	25.3	−2.2	26.8	−2.2	21.8	−.3	15.7	−3.0	10.8	.5	8.9	.2
6847	18.1	55.0	26.8	.1	29.2	−2.1	21.1	−.2	26.8	−2.3	27.5	−2.1	23.7	.3	11.8	−3.2	9.1	−.1	7.9	−.2
HOUSTON BLACK CLAY, TEMPLE, TEX.																				
6696	10.7	41.5	44.9	2.9	35.6	−2.2	29.5	−2.7	29.1	−6.0	29.2	−4.6	30.5	−1.5	18.9	−1.8	15.1	−0.3	12.2	−0.7
6697	8.9	42.6	46.6	1.0	38.5	.1	29.6	−1.5	28.1	−7.5	27.5	−6.8	27.6	−4.4	17.8	−3.5	16.5	.8	12.6	−1.5
6698	10.1	44.7	41.1	1.1	33.6	−3.4	26.0	−2.9	25.4	−9.6	25.2	−8.2	24.4	−6.0	15.6	−5.4	13.1	−1.7	10.6	−2.3
6699	13.9	49.4	36.2	.5	28.5	−4.5	20.7	−4.5	21.1	−8.2	21.1	−6.5	20.6	−6.5	13.5	−6.2	11.1	−1.3	8.0	−2.7
MARSHALL SILT LOAM, CLARINDA, IOWA																				
B171	2.5	61.9	32.4	3.2	32.3	−0.4	28.4	−1.0	36.1	3.7	35.1	3.6	30.2	0.4	22.6	3.6	10.1	−1.0	8.6	−0.7
B172	1.8	61.3	34.6	2.3	36.7	3.2	30.1	+1.6	38.1	7.0	36.5	4.2	31.8	2.2	22.4	2.8	13.1	.7	10.2	.2
SHELBY SILT LOAM, BETHANY, MO.																				
6797	25.3	47.2	24.3	3.2	26.2	−1.2	21.7	−0.7	31.3	3.9	29.9	3.6	21.5	0.2	19.6	3.1	8.7	−0.0	6.9	−0.2
6798	18.9	30.2	48.7	2.2	41.1	2.3	33.9	2.3	34.2	−1.1	30.7	−2.9	34.0	3.5	19.8	−1.4	17.5	1.3	14.8	.7
6799	19.7	33.3	45.4	1.6	40.8	3.7	32.9	3.4	33.8	−.5	31.6	−.9	34.2	4.3	17.6	−3.1	17.0	1.9	14.7	1.5
6800	30.5	30.9	37.8	.8	33.0	.3	29.0	3.9	29.4	−1.5	26.1	−2.7	27.1	1.6	14.8	−4.3	12.9	.3	11.1	−.4
6801	31.9	35.1	29.7	.3	27.0	−1.6	23.0	2.4	27.1	−.9	21.0	−1.9	23.0	.8	12.3	−5.3	10.5	.3	8.0	−1.0
6802	33.2	35.7	31.0	.1	25.5	−3.7	22.0	1.2	26.0	−2.6	21.6	−1.9	22.9	.4	11.4	−6.5	9.4	−1.1	8.0	−1.4
6802a	61.7	19.6	18.5	.2	17.3	−4.3	15.2	−1.0	17.7	−3.9	13.7	−5.5	16.1	.9	11.4	−3.1	6.2	−.3	4.9	−1.1
6802b	34.6	34.7	30.6	.1	25.7	−3.2	22.8	1.4	25.1	−3.2	22.8	−3.1	23.5	1.2	12.8	−5.0	9.2	−1.2	8.1	−1.2

CLINTON SILT LOAM, LA CROSSE, WIS.

10362	6.5	80.6	11.2	1.7	25.8	3.6	22.0	2.0	(4)		(4)		23.9	2.1	(5)		5.4	−0.1	4.1	0.6
10363	7.1	74.0	18.8	.1	26.6	1.3	20.6	1.0	(4)		(4)		23.5	.9	23.0	5.9	7.8	.4	6.0	.2
10364	7.2	71.0	21.8	.0	30.3	3.7	22.1	1.8	32.8	3.9	32.7	5.2	21.7	1.3	20.9	3.3	8.9	.6	7.4	.7
10365	11.1	70.7	18.2	.0	28.1	3.4	19.8	.9	31.1	3.8	30.5	4.6	22.4	.6	20.7	3.8	7.8	.6	6.3	.6
10366	69.2	9.4	21.4	.0	19.4	−3.0	16.2	.0	18.1	−3.5	18.1	−.9	13.8	−1.0	11.5	−3.1	7.7	.5	5.9	−.9

PALOUSE SILT LOAM, PULLMAN, WASH.

8069	6.3	67.5	21.0	2.2	27.3	−0.9	23.2	−1.6	30.9	1.4	30.7	2.1	25.1	−0.9	18.8	1.2	9.6	−0.3	7.9	0.8
8070	5.9	59.3	33.8	1.0	32.8	.3	25.5	−.3	33.2	.7	30.7	−.4	27.8	−.1	18.0	−1.5	13.6	1.7	10.6	.7
8071	5.9	61.6	32.0	.5	33.1	1.6	28.4	2.0	32.7	.7	31.1	.6	27.6	.7	17.7	−1.6	13.5	2.2	10.7	1.2
8072	6.8	66.2	26.6	.4	28.7	.3	22.8	.3	29.6	−.7	28.8	−.1	25.5	.3	17.5	−.9	10.9	1.2	9.1	1.1
8073	6.5	67.3	25.9	.3	26.9	−1.7	23.5	1.4	30.1	.0	27.7	−1.0	25.5	.6	17.9	−.4	10.0	.5	9.2	1.4

VERNON FINE SANDY LOAM, GUTHRIE, OKLA.

6718	72.0	21.0	5.2	1.8	16.3	1.1	13.2	−1.0	(4)		(4)		.6	1.6	(5)		2.7	−0.2	2.2	0.1
6719	74.5	15.0	9.9	.6	15.9	−1.0	11.9	−1.5	(4)		(4)		9.1	−2.1	(5)		3.3	−.7	2.5	−1.1
6720	60.1	15.5	23.8	.6	22.3	−2.0	18.6	.0	20.9	−2.5	19.2	−1.8	17.7	.5	16.1	.8	7.8	−.4	6.4	−1.0
6721	32.7	39.0	27.4	.3	25.4	−2.2	20.7	−.2	28.0	.4	26.1	.5	18.4	−3.4	11.3	−3.0	8.0	−1.5	7.8	−2.5

MUSKINGUM SILT LOAM, ZANESVILLE, OHIO

B407	6.5	71.7	19.9	1.9	26.2	−0.1	23.1	0.1	(4)		(4)		25.5	1.0	(5)		7.6	−0.5	6.3	0.4
B408	9.4	63.0	27.3	.3	29.9	.8	21.5	−.9	37.0	6.8	34.2	5.0	26.2	1.3	23.1	4.7	9.6	−.2	9.1	.9
B409	21.3	53.4	25.3	.0	28.6	1.3	19.3	−1.2	(4)		(4)		21.0	−1.5	21.8	7.2	8.6	−.4	8.2	.5
B410	25.2	54.5	20.3	.0	24.6	−.2	16.7	−2.0	(4)		(4)		19.4	−1.1	21.3	4.8	6.2	−1.4	5.7	−.6
B411	18.0	63.0	19.0	.0	23.0	−1.0	14.2	−4.6	(4)		(4)		19.8	−1.3	(5)		5.7	−1.6	5.2	−.7

KIRVIN FINE SANDY LOAM, TYLER, TEX.

6678	75.5	18.4	5.6	0.5	16.3	1.5	10.1	−1.8	(4)		(4)		7.9	−1.9	(5)		2.5	−0.2	1.8	−0.6
6679	31.0	8.8	59.4	.8	48.9	6.2	33.0	1.2	42.6	5.5	40.4	5.7	30.5	−1.2	29.0	6.3	16.9	−4.0	16.9	−.4
6680	36.8	13.0	50.0	.2	41.3	3.5	28.5	1.0	38.6	4.9	36.4	5.2	28.5	.8	23.5	2.5	15.3	−.6	14.8	.1
6681	51.3	16.3	32.3	.1	27.9	−.7	18.7	−2.2	30.6	3.7	28.1	3.7	21.2	.7	17.8	.5	9.2	−1.4	9.8	.0
6682	88.0	4.7	7.3	.0	19.5	4.8	13.2	2.5	(4)		(4)		6.7	−1.4	(5)		3.0	.1	3.0	.0

See footnotes at end of table.

TABLE 7.—*Soil-moisture constants and related data of the soils from the erosion experiment stations*—Continued

NACOGDOCHES FINE SANDY LOAM, TYLER, TEX

Sample no.	Sand	Silt 2µ-50µ	Clay < 2µ	Organic matter	Minimum water of saturation		Normal moisture capacity		Sticky point		Sticky point (10 cm per second)		Moisture equivalent		Lower plastic limit		Centrifugal moisture		Water-vapor absorption	
					Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals	Determined	Residuals
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
9475	70.0	11.7	18.1	2.2	20.3	-0.2	18.0	-0.4	(4)		(4)		11.3	-0.7	(5)		6.5	0.4	5.5	0.4
9476	46.0	6.2	47.1	.7	30.7	-7.3	26.0	-.8	28.0	-3.8	26.2	-3.0	25.2	-.8	20.1	0.2	15.4	.3	15.0	1.1
9477	55.2	6.6	38.2	.0	30.8	5.7	26.0	4.6	(4)		(4)		25.1	3.5	24.3	6.2	15.6	3.4	15.6	4.1
9478	64.9	3.4	31.7	.0	28.1	.6	18.3	-1.4	31.5	6.4	28.0	5.6	18.6	.2	20.0	3.1	9.0	-.3	9.8	.1
9479	60.4	6.9	32.7	.0	31.2	3.0	20.8	.5	(4)		(4)		22.5	3.2	(5)		13.3	2.7	13.5	3.5

CECIL SANDY CLAY LOAM, STATESVILLE, N. C.

Sample no.	Sand	Silt 2µ-50µ	Clay < 2µ	Organic matter	Minimum water of saturation: Determined	Residuals	Normal moisture capacity: Determined	Residuals	Sticky point: Determined	Residuals	Sticky point (10 cm per second): Determined	Residuals	Moisture equivalent: Determined	Residuals	Lower plastic limit: Determined	Residuals	Centrifugal moisture: Determined	Residuals	Water-vapor absorption: Determined	Residuals
6977	54.1	28.4	17.3	3.2	21.4	-1.1	23.0	1.1	(4)		(4)		20.0	-1.3	(5)		7.7	0.8	6.0	0.7
6978	30.8	17.5	51.2	.5	35.4	-3.4	31.7	4.0	38.3	3.5	35.4	3.0	26.6	2.5	24.9	3.5	11.8	-1.6	13.6	-1.4
6979	25.8	25.3	48.6	.3	38.0	.1	25.6	-2.3	42.1	7.8	40.5	8.2	25.7	-.2	26.9	5.7	15.6	-.1	14.9	.6

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[1] Determined value minus value computed from normal equation. These computations were furnished by W. E. Deming.

[2] At a shearing speed of 5 cm per second.

[3] At a shearing speed of 10 cm per second.

[4] Not sticky.

[5] Not plastic.

The lowest value obtained, 15.9 percent, was for a fine sandy-textured horizon of the Vernon. The calculated porosity, based upon the specific gravity datum of Middleton, Slater, and Byers (*24*) and assuming the voids were completely filled with water at unit density, was 29.7 percent. This is considerably less than the porosity, 41.7 percent, of their field sample but greater than the 26 percent required for uniform-size spheres arranged in closest packing. Prescott and Poole (*25*) obtained porosities of sand and silt mixtures as low as 12 percent. There is no certainty in this work that part of the pore space was not filled with air. The highest value obtained for the minimum water of saturation was for the B horizon of the Kirvin. For this sample the calculated porosity was 57.9 percent. The porosity in field condition was 53.4, and at settling volume it was 74.3. The average porosity of the heaviest clay samples, of which only one was a surface layer, was nearly the same as that of the soils in field condition, but considerably lower than the porosity at settling volume.

These comparisons for clay soils are of interest in connection with any discussion of the merit of this test in the case of fine-textured soils. The deflocculation caused by manipulation during test is favorable to the formation around the individual clay particles of water envelopes which, in the absence of external compressive forces, may become relatively thick. This would lead to abnormally high values of the minimum water of saturation. Although it cannot be shown that this effect does not occur, the porosity of the sample at the minimum water of saturation cannot be regarded as greatly excessive when the volume weight is approximately the same as that of the same subsurface material in the condition of field packing. For all but a few of the finest textured soils the porosity of the test samples was less than that of the field soils.

RELATIONSHIPS OF THE SOIL-MOISTURE CONSTANTS

This statistical study is an attempt to find general relationships among the soil-moisture constants and other physical or chemical properties. Although there are only 52 samples in the set, they cover so wide a range of physical and chemical characteristics that generalizations which hold for the entire group may be accepted with more confidence than if they were based, as is so often the case, on soils of a single great soil group. Some of the samples, as has already been noted, have unusual particle-size distribution. The lateritic clays and the Houston have physical properties quite different from those of the other soils.

In order to express the texture of these soil samples in the simplest significant form the fractions obtained in mechanical analysis were regrouped into four classes. The organic matter was determined by the hydrogen peroxide method in the routine pretreatment of the samples for mechanical analysis. The clay consists of inorganic material less than 2μ in diameter, designated in the reports of Middleton, Slater, and Byers (*23, 24*) as colloid. The material from 2μ to 50μ in diameter is silt. The sand content was obtained by difference, so that the sum of the four constituents was 100 percent in each

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[4] Acknowledgment is gratefully made to W. E. Deming, in charge of mathematical and statistical analysis, Fertilizer Research Division, Bureau of Chemistry and Soils, for advice and assistance in the preparation of this section of the bulletin, for the solution of the normal equations given on p. 38, and for the computation of the residuals given in table 7.

instance. Small changes in the percentage of sand affect the values of the constants less than an equal change in any of the other constituents.

On the assumption that the soil-moisture constants are functions of the unweighted values of the sand, silt, clay, and organic matter contents of the soils, observations ranging from 38 to 52 in number were set up, and the values of the coefficients of the silt, clay, and organic matter (o. m.) were computed by the method of least squares. The solutions obtained were:

1. Moisture equivalent = 4.4 + 0.130 (silt) + 0.427 (clay) + 0.96 (o. m.) ± 1.4.
2. Centrifugal moisture = 0.63 + 0.15 (silt) + 0.301 (clay) + 0.21 (o. m.) ± 0.8.
3. Water-vapor absorption = 0.95 − 0.005 (silt) + 0.278 (clay) − 0.10 (o. m.) ± 0.8.
4. Minimum water of saturation = 10.5 + 0.065 (silt) + 0.527 (clay) + 0.31 (o. m.) ± 1.8.
5. Normal moisture capacity = 7.7 + 0.063 (silt) + 0.371 (clay) + 1.79 (o. m.) ± 1.3.
6. Sticky point (s. p. 5) = 11.8 + 0.115 (silt) + 0.408 (clay) + 0.08 (o. m.) ± 2.9.
7. Sticky point at 10 cm/sec. (s. p. 10) = 8.9 + 0.135 (silt) + 0.409 (clay) + 0.31 (o. m.) ± 2.7.
8. Lower plastic limit = 9.6 + 0.047 (silt) + 0.216 (clay) − 0.17 (o. m.) ± 2.6.

The limits given in the equations are the probable errors of single observations. The organic-matter coefficients have high probable errors due to the low percentages of this constituent present in most samples. Its effect upon the moisture constants may be masked almost completely by such factors as variations in particle-size distribution within the size classes and variations in the chemical character of the clay, as well as by experimental errors. In the solutions of the normal equations it appears that additional weights might well have been given both to the clay and to the organic-matter percentages, but it was not certain what values should have been chosen. Experience indicates that in all the equations the organic-matter coefficients should be positive and probably at least as large as the clay coefficients.

The probable error of the moisture-equivalent equation is smaller than that obtained by Middleton (*22*). This may be due in part to differences in the degree of dispersion and in the silt and clay size limits or to the separation of the organic matter into a separate class in one case and not in the other. Middleton found that his equation did not fit so well for soils high in organic matter. Prescott and Poole (*25*) obtained equations which fit very closely when data from only closely related soils were used. The magnitude of the probable errors indicates that one can compute the centrifugal moisture and the water-vapor absorption fairly precisely from the mechanical analyses but that this is not true for the sticky point and lower plastic limit. The normal equations indicate that the moisture equivalent, minimum water of saturation, and normal moisture capacity are controlled chiefly by the mechanical composition.

For all constants of all horizon samples of the Clinton except the lowest, which is a sandy clay differing greatly in texture from the other samples, the significant residuals are positive. For the Houston profile samples the residuals are large and negative. Why the moisture constants of this heavy clay are of about the same value as other soils of coarser texture is not known to the writer. The unusually large quantity of very fine silt, 2μ to 5μ in diameter, might be expected to raise the value of the moisture constants. Perhaps the cause is to be found in the unusual chemical composition. Over 60 percent of the material of this profile consists of calcium carbonate.

The colloid is very high in exchangeable calcium but low in exchangeable magnesium. The large negative residuals of the sticky point and lower plastic limit indicate that the soil is highly plastic.

In order to determine whether the moisture constants were simply related to other physical soil properties, a preliminary survey was made by means of scatter diagrams of the constants plotted against other available data. In the first part of table 8 are presented the simple coefficients of correlation between the moisture constants and laboratory volume weights and settling volumes. These were the only other physical properties which, according to the scatter diagrams, appeared to be significant. The same table contains the correlation coefficients of pairs of the moisture constants themselves.

TABLE 8.—*Correlation coefficients of the soil-moisture constants and constant residuals from data of the erosion station soils*

SOIL-MOISTURE CONSTANTS

Soil property	Minimum water of saturation	Normal moisture capacity	Sticky point	Sticky point (10 cm per second)[1]	Moisture equivalent	Lower plastic limit	Centrifugal moisture	Water-vapor absorption
Minimum water of saturation		0.90	0.78	0.78	0.87	0.61	0.92	0.91
Normal moisture capacity	0.90		.59	.59	.93	.37	.88	.82
Sticky point	.78	.69		.98	.74	.89	.58	.66
Sticky point (10 cm per second)[1]	.78	.59	.98		.74	.91	.57	.63
Moisture equivalent	.87	.93	.74	.71		.43	.85	.78
Lower plastic limit	.61	.37	.89	.91	.43		.39	.53
Centrifugal moisture	.92	.88	.58	.57	.85	.39		.96
Water-vapor absorption	.91	.82	.66	.63	.78	.54	.96	
Laboratory volume weight	−.72	−.73	−.50	−.55	−.65	−.44	−.69	−.70
Settling volume	.93	.97	.16	.10	.95	.15	.90	.86
Exchangeable bases (colloid)	−.16	−.39	−.45	−.38	−.39	−.59	−.24	−.38
Silica-sesquioxide ratio (colloid)	.17	.20	−.38	−.27	.12	−.57	−.08	−.22

SOIL-MOISTURE CONSTANT RESIDUALS

Soil property	Minimum water of saturation	Normal moisture capacity	Sticky point	Sticky point (10 cm per second)[1]	Moisture equivalent	Lower plastic limit	Centrifugal moisture	Water-vapor absorption
Minimum water of saturation		0.54	0.60	0.60	0.47	0.57	0.43	0.60
Normal moisture capacity	0.54		.10	.07	.32	−.05	.59	.48
Sticky point	.60	.10		.95	.50	.74	−.01	.45
Sticky point (10 cm per second)[1]	.60	.07	.95		.38	.57	.06	.46
Moisture equivalent	.47	.32	.50	.38		.26	.59	.72
Lower plastic limit	.57	−.05	.74	.57	.26		.02	.48
Centrifugal moisture	.43	.59	−.01	.06	.56	.02		.77
Water-vapor absorption	.60	.48	.45	.46	.72	.48	.77	
Laboratory volume weight	−.41	−.37	−.28	−.27	−.32	−.27	−.31	−.42
Settling volume	−.15	.22	.01	−.04	.18	−.16	.00	−.01
Exchangeable bases (colloid)	−.32	−.01	−.76	−.75	−.35	−.70	−.00	−.38
Silica-sesquioxide ratio (colloid)	−.23	.02	−.53	−.52	−.22	−.61	−.13	−.35

[1] At a shearing speed of 10 cm per second.

Since the normal equations show that all the moisture constants can be represented within limits as somewhat similar functions of the mechanical composition, it is to be expected that the correlations between the constants themselves should be rather high. The highest correlation, 0.98, is the one between the two sticky points. One may assume that this would have been a perfect correlation had there been no experimental errors in the sticky-point data. There is also a high correlation, 0.96, between the centrifugal moisture and water-vapor absorption at 99 percent relative humidity. The correlation between the sticky point and the lower plastic limit is relatively high, but the correlations between these two constants and the others are without exception the lowest of the entire group. This differentiation of the two moisture constants associated with soil plasticity from the other five is shown even better by the settling-volume correlations, all five being much greater. These correlations are based upon data from only the surface and subsoil layers of each soil, 22 samples in all.

The negative correlations between the laboratory volume weights, which were obtained in the course of the normal moisture-capacity determinations, and the moisture constants probably have little significance other than that the sandier soils generally have the higher volume weights. The correlation between the clay content and laboratory volume weight is −0.71, but between the clay content and field volume weight it is only −0.37.

Because of the dominant influence of texture, one might expect to find high correlations among the moisture constants. There is, however, no reason to expect any correlation between texture and the chemical composition of the extracted colloid. If there are significant relationships between the moisture constants and any quantitative chemical data the correlations usually may be expected to be masked by the stronger influence of texture upon the moisture constants. Scatter diagrams were made of the moisture constants plotted against a wide variety of chemical data of both the whole soil and the extracted colloids. The only diagrams which indicated the possibility of significant correlations were those in which the silica-sesquioxide ratios and exchangeable-base contents of the extracted colloids were employed. Correlation coefficients involving these data also are presented in table 8.

Most of these correlations are low, but the preponderance of negative values indicates a tendency for the moisture constants to be high in the lateritic soils. The highest of these correlations involve the lower plastic limit and the sticky point. Although these four coefficients are not large, they exceed the correlations between the lower plastic limit and some of the other physical properties in which texture is presumed to be the dominant factor. Scatter diagrams made by plotting the silica-sesquioxide ratio or the exchangeable-base content against the sticky point-moisture equivalent ratio indicate the existence of significant negative correlations between this ratio and the chemical properties. In these data the ratio of sticky point to moisture equivalent averages 1.24, with an average deviation of 11 percent. Bodman and Perry (*6*) found that sticky point=moisture equivalent ±10 percent. In this investigation the higher ratio may be due to differences in the sticky-point procedures or in the samples used. The ratio is high for lateritic soils and lowest for the most plastic soils.

The correlation between the sticky point by the roller method and the moisture equivalent is 0.74. Prescott and Poole, who employed adhesion tests except for the heaviest soils, obtained a value of 0.93 for the same correlation. It seems improbable that their sticky-point data would yield as high a correlation to the lower plastic limit as the value 0.89 obtained in this work, because the correlation between the lower plastic limit and the moisture equivalent is only 0.43. The close relationship of the sticky point by the roller method and the lower plastic limit has been shown by the data of table 8 and again will be pointed out later. Because of this association it is the writer's opinion that either the sticky point should be determined by a standardized and mechanized shearing method, or a new moisture constant, called the scouring point, should be determined by this procedure.

A set of correlation coefficients involving the same soil properties as the coefficients presented in table 8 were computed. In these computations, instead of the values of the moisture constants themselves, the residuals given in table 7 were used. The underlying assumption is that the normal equations give the true relation between the moisture constants and mechanical composition and that the residuals are due to causes other than differences in texture. The residuals are so heavily loaded with experimental error that the coefficients probably are not highly significant. Furthermore, the subdivision of mechanical composition into the four classes employed cannot accurately represent texture unless there is for all soils an identical particle-size distribution within each of the grades selected. This condition, of course, is not fulfilled.

The correlation coefficients of the moisture constant residuals are presented in the second part of table 8. Notwithstanding the expectancy of excessively large errors the correlation between the two sticky points is 0.95. The settling-volume coefficients, all small and some positive and some negative, indicate that the settling volume is dependent primarily upon texture. The correlation coefficients between the centrifugal moisture and water-vapor absorption, given in table 8, is 0.96, and the coefficient of their residuals is 0.77. These moisture constants appear to be as closely related to each other as are the sticky point and the lower plastic limit.

The correlation coefficients between the residuals and the two sets of chemical data, although low, are negative, indicating that the chemical composition of the colloid slightly affects all the moisture constants. The highest of these negative correlations, involving the sticky point and the lower plastic limit, indicate that soil plasticity is influenced to a greater degree by the chemical composition of the colloid than are the other moisture constants. The marked effect of sodium hydroxide upon the sticky point and lower plastic limit of lateritic soils experimentally confirms the statistical evidence that the soil plasticity to some degree antiparallels the exchangeable-base content of soils.

It is rather surprising that the correlation coefficients, particularly those using the residuals, do not indicate a stronger influence of the chemical nature of the colloids upon the nonplastic moisture constants. For instance, in the case of these same soils, it has been shown by Middleton, Slater, and Byers (*24*) that the settling volumes of the extracted colloids fall in the same order as the silica-sesquioxide ratios. In determinations of some of the moisture constants of extracted soil colloids, planned for a later investigation, undoubtedly it will be found that the chemical character of the material has a marked influence. The failure of the chemical properties of the colloids to show, in this investigation, a stronger influence upon the soil-moisture constants may be due to the actual dominant influence of texture; but it may also be due in part to the failure of the particle-size classification employed to represent the soil texture with sufficient accuracy.

SUMMARY

Studies of the relationships of seven soil-moisture constants, including the three new ones, centrifugal moisture, minimum water of saturation, and normal moisture capacity, of the soils of the soil-erosion stations of the United States Department of Agriculture are reported.

The centrifugal moisture, which is the moisture held by soil material when centrifuged in a small bearingless air-driven centrifuge at 300,000 gravity, has a slightly higher average value than the water-vapor absorption at 99 percent relative humidity but probably a somewhat lower value than the permanent wilting percentage. The data presented indicate that the moisture equivalent should not furnish a reliable measure of the permanent wilting percentage of soils.

The normal moisture capacity, for the determination of which a procedure is given, appears to furnish a more accurate measure of the field capacity of soils than does the moisture equivalent.

The sticky-point data obtained by adhesion tests may differ considerably from those obtained by shearing methods. A simple roller device, applicable to plastic soils only, is presented and recommended as a basis for a standardized sticky point or scouring-point procedure of the shearing type. The addition of small quantities of sodium hydroxide lowered the sticky point and lower plastic limit of lateritic and noncalcareous soils.

Procedures are given for the determination of the minimum water of saturation, which is the percentage of water required to saturate a soil sample when the soil grains are arranged in position of closest packing. The test is made most accurately and easily for nonplastic soils. The average value is slightly lower than that for the sticky point, but it is more closely related to the clay content than are the other moisture constants.

A statistical study of soil-moisture constant data shows the centrifugal moisture and water-vapor absorption at 99 percent relative humidity to be closely related, as also are the lower plastic limit and the sticky point. The data indicate that the minimum water of saturation, normal moisture capacity, moisture equivalent, centrifugal moisture, and water-vapor absorption are controlled chiefly by the mechanical composition of the soil and run parallel to the settling volume. The lower plastic limit and the sticky point are not so closely related to texture, and are influenced to a greater extent by the chemical character of the colloid than are the other moisture constants.

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