THE CRUSHING STRENGTH OF FRAGMENTED SOIL MATERIAL IN RELATION TO MOISTURE CONTENT AND OTHER PHYSICAL PROPERTIES OF THE SOIL

by

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INTRODUCTION

For centuries man has been interested in the physical condition of the soil. Color and other physical properties of the soil were recognized early as being related to its productivity. The first plow, however crude it may have been, was developed because of this recognition of the relationship between the physical condition of the soil and crop production.

The field of soil physics, however, or the actual laboratory analysis of the physical properties of the soil, is a development of the last half century, and more particularly of the last 25 years. Within this time many different types of analyses have been employed in an attempt to learn more about the character of that extremely variable and life-giving complex, the soil, in order that man might know how best to manage the soil for its greatest usefulness. Many of these properties contribute to what is known as soil structure, regarding which Russell (1938) says:

> One of the fundamental duties of any agricultural system is to keep the soil structure in reasonable control, and it is probably no exaggeration to say that nearly every system of crop husbandry that has failed has also failed to control the structure. . . The methods available for structure control can be divided into four classes, namely the proper use of the climate, of cultivation implements, of additions of manures and of the growing plant.

A soil is commonly classified as a sandy loam or a silty clay loam etc. on the basis of the size distribution of the primary particles (sand, silt and clay). This does not give a complete picture of the soil by any means, however, for these primary particles may be and usually are bound into larger aggregates which will have a marked influence on such properties as density, porosity, and infiltration.

Because certain air and moisture relationships are essential to plant growth one of the criteria by which soils are sometimes measured is that of porosity--the number, size and distribution of the pore spaces.

Water-stable aggregation is another measure of the condition of the soil. It is greatly influenced by such factors as clay content, organic matter content, tillage operations and the crops grown.

Since cropping systems, meaning here both the crops produced and the tillage operations entailed in such production, are considered to influence the structure of the soil, the question naturally arises as to whether there is any correlation between the cropping system which has been followed and any of the present physical properties of the soil. The research recorded here was an attempt to discover whether the physical property of the crushing strength of fragmented soil material could be used to distinguish between plots which had been under different cropping systems and also to determine what relationship the crushing strength might bear to other properties of the soil such as moisture content, water-stable aggregation, nitrogen content and volume weight. Crushing strength is defined in this study as the ratio of the force in ounces required to shatter an aggregate divided by its weight in milligrams.

REVIEW OF LITERATURE

A diligent search through agricultural, chemical and other abstracts failed to reveal any reference to work of a quantitative nature on the crushing strength of unconfined soil fragments, although many hypotheses have been proposed regarding factors which bind the soil and may influence its resistance to crushing.

Some work has been done on the crushing strength of granulated fertilizer material, such as that of Hardesty and Ross (1938). Conditions are not identical, of course, between that and the present study, for the crushing characteristics of a spherical fertilizer pellet differ from those of an irregularly shaped fragment of soil material; but the crushing technique is the same so that some comparisons may be applicable.

One of the factors influencing the stable structure and the hardness of a soil is the moisture content at which it is worked, much of this type of study having been conducted by workers in Russia. Usually the work was done by kneading a fine soil (one which would pass a ¼ mm sieve) at various moisture contents. Vassilenko and Setzinsky (1933) and Vilensky and Germanova (1934), cited by Russell (1938), found that at the "moisture content for optimum structure formation" the aggregates which were formed had both maximum water stability and maximum mechanical strength. Russell's review did not mention whether this maximum mechanical strength was measured quantitatively. Hénin (1936) showed the optimum moisture content for the fine sandy loam of Versailles to be near the sticky point. In this connection Russell (1938) says that:

> If the moisture content is too high the soil, when it is cultivated, may be left badly poached and will tend to dry out into large hard clods. If the moisture content is too low the main effect of the cultivation will be that some of the existing aggregates will be broken or shattered by the implement and little or no structure built up.

Russell presents the following data taken from the work of Tsyganov (1936) which bear out the point regarding cultivation at low moisture content versus cultivation at optimum moisture content. It also illustrates the effect of discing as versus plowing in regard to structure formation.

Effect of cultivation on the percentage of field aggregates and water-stable aggregates

Soil cultivated near	Field aggregates				Water-stable aggregates			
	wilting point		field capacity		wilting point		field capacity	
Aggregates' size in mm	>5	<¼	>5	<¼	>5	<¼	>5	<¼
Before cultivation	40	21	12	30	48	22	13	40
After 2 plowings and 4 discings	20	16	33	11	54	19	44	24
After 2 plowings and 20 discings	16	28	40	11	39	28	30	31

Various cementing agents are present in the soil causing aggregation and influencing the strength and water stability of these aggregates. Lutz (1937), working on the effect of free iron as an important factor influencing granulation in lateritic and semi-lateritic soils, says, "The free iron probably serves a dual purpose, the part which is in solution functioning as a flocculating agent and the other as a cementing agent."

Baver (1935) has studied the influence of organic matter and of clay content on soil aggregation. Either factor was shown to have a fairly high correlation with aggregation if the other factor was held low. This work was done on 77 different soils (exclusive of lateritic soils) throughout the United States. Regarding his findings, Baver says, "it seems that the organic matter in soils is one of the major causes of stable soil aggregation. The clay content also plays an exceedingly important part." It does not follow necessarily, however, that these factors which influence granulation will have a related effect on crushing strength.

Russell (1935) has postulated a binding force called the dipole-cation-dipole linkage which holds the particles together: the cations are the exchangeable cations of the clay colloid; the dipoles in the linkage are the oriented molecules of the dipolar dispersion medium which are present when dealing with a clay paste (the most common dispersion medium is water). The effectiveness of the dipole-cation-dipole linkage in binding depends upon (1) the number, size and charge of cations which are dissociated from the clay particles; (2) the presence of a polar dispersion medium; (3) the size of the clay particles and (4) the concentration of the dispersion medium. In regard to the first condition, Russell found that crumbs could not be formed from fine Kaolin clay when it was of low exchange capacity (e.g., less than 20 milliequivalents per 100 grams of soil). Regarding the second condition, when a paste was formed with benzene (a non-polar medium) and dried no crumbs were formed. As for the third condition Russell says, "Hard crumbs can be produced only from clay particles smaller than 1 μ in diameter." With respect to the fourth condition, according to Russell's theory, as the clay paste dries the linkage will become stronger, for the oriented polar water molecules have a lesser charge than the cations and clay particles: thus, as the oriented polar water molecules are evaporated, the linkage between cations and clay particles becomes shorter and therefore stronger.

MATERIAL AND METHODS

Crushing Equipment and Technique

The crushing equipment which was used in this experiment was supplied by the Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture, and is the same as that developed by them for use in studying the hardness of fertilizer pellets. It consisted of household scales of the spring platform type, essentially the same as those illustrated in Fig. 1, equipped with a small platform onto which descended a plunger operated by a rack and pinion. The dial had both the regular indicator needle and a follower hand which remained at the point where the crush occurred. The range of the scales was 25 pounds or 400 ounces.

Fragments to be crushed were placed in a two-inch aluminum moisture can on the platform of the scale. The plunger, operated manually, was lowered to the fragment and then lowered slowly at a uniform rate until the fragment was crushed. Particles were so oriented for crushing as to avoid side thrusts in order that the shatter come all at once rather than in increments. The desired end point was a complete shatter, but frequently this was hard to attain, especially when working with moist samples.

Source: photograph courtesy J. O. Hardesty.

There was great variability in the crushing strengths due to the irregularity in shape of the aggregates being crushed. Hardesty and Ross (1938) found that the average crushing load required for spherical granulated fertilizer pellets was considerably less variable than that for irregularly shaped pellets of the same weight. Selection of individual fragments for crushing was therefore not completely randomized in that those aggregates which had one axis considerably longer or shorter than the other two axes were rejected.

In the moisture relation studies, it was necessary to conduct the crushing under conditions that would lead to as little loss or gain of moisture as possible. Oven dry and air dry samples were crushed under ordinary room conditions of midsummer, which, in spite of low relative humidity, meant a fairly high absolute humidity. In order to prevent any more gain of moisture than was absolutely necessary, the oven dry fragments were kept in a desiccator and returned to the desiccator as quickly as possible after crushing. No special treatment was necessary for the air dry samples. For samples at field moisture, samples in partial equilibrium with saturated air and samples at a slightly higher water content than those in partial equilibrium with saturated air, a cubicle was adapted in which the work could be conducted under conditions of near 100 per cent humidity. The cubicle was built on a table at waist height and was large enough to accommodate the crushing equipment and humidors and still permit the operator to work freely with head and shoulders inside the front curtain. High humidity was maintained by keeping the curtains and interior walls soaked with water and also having an air operated atomizer spraying a fine mist within the cubicle.

The fragments from the Hays core samples were crushed under ordinary laboratory conditions.

Attention should be called to the meaning of the expression "crushing strength" as used in this study. In order to reduce the variation of a given size range which occurs from one sample to the next because of the unequal distribution of the individual particles within the size range, crushing strength is given as the ratio of the average force required to crush a set of fragments (expressed in ounces) divided by their average weight (expressed in milligrams). This ratio is based on the assumption that the crushing strength varies directly with weight, which, while not strictly true, is nearly enough true to justify the use of the ratio in reducing variations in the data.

In the moisture studies a further step was taken. It was found that the standard deviation of the mean force required to crush 20 particles varied directly with the mean. This is illustrated in Fig. 3. For ready interpretation of the data all points should have about the same standard deviation. This means that a transformation had to be made. The fact that the free-hand line drawn through the points in Fig. 3 passed through the origin suggested that this transformation might be fairly simple. Transformation was made by using the logarithm of the force required to crush each fragment and then computing the mean logarithm and the standard deviation of the mean. The result is illustrated in Fig. 2 (data used in preparing Figs. 2 and 3 are found in Table 1). Figure 2 shows a definite scatter when standard deviation is plotted against the mean. Hence, in all the moisture relation studies log F.C./log wt. will indicate the ratio of the mean of the logarithms of the actual force required to crush divided by the logarithm of the average weight of the particles.

For the study of relationships other than moisture content, crushing strength will indicate the ratio of the mean of the actual forces required to crush the fragments divided by the average weight. It was not considered necessary to make the transformation because only one size particle was used

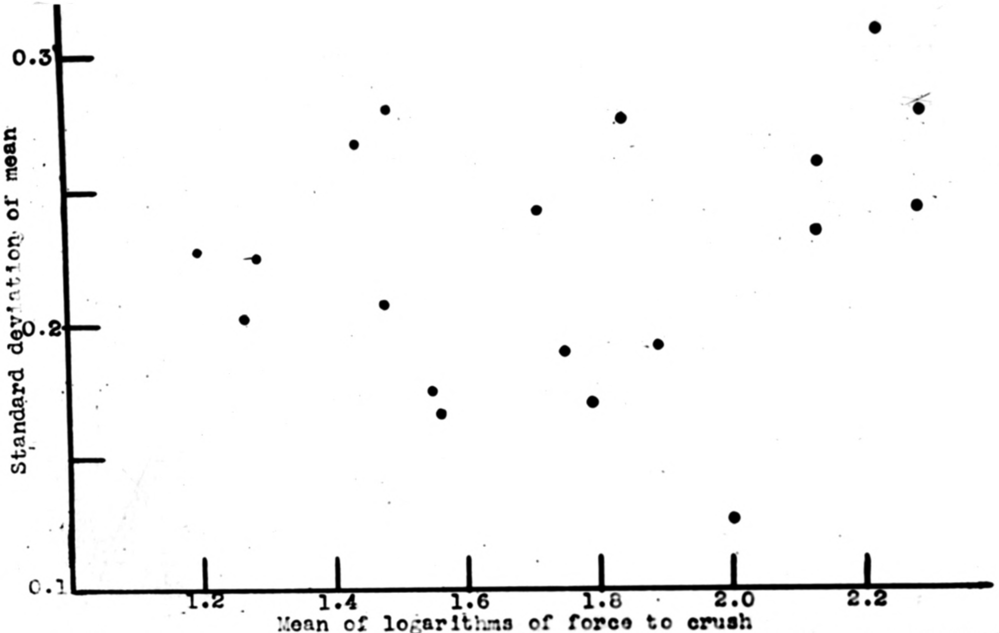


Fig. 2. Scatter diagram of the standard deviation of the mean plotted against the means of the logarithms of the force required to crush the different sized fragments from the Hays surface soil (Munjor 0-5) at various moisture contents.

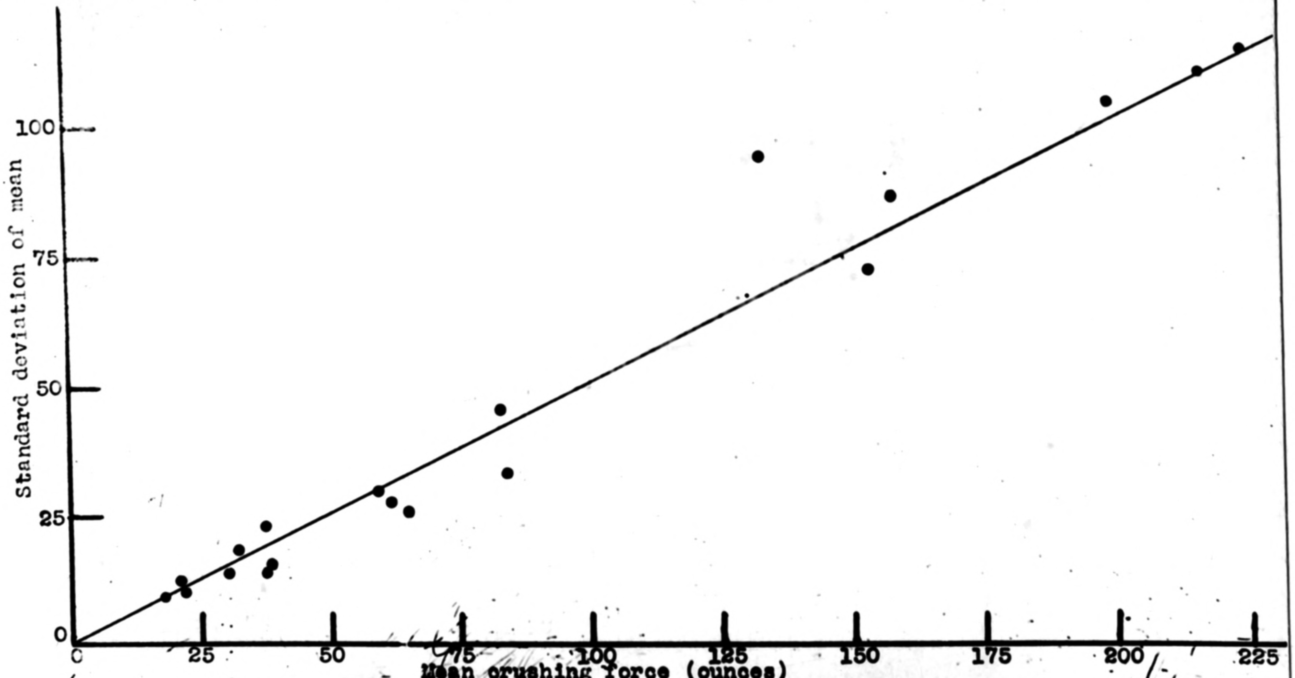


Fig. 3. Scatter diagram of the standard deviation of the mean plotted against the mean crushing force (in ounces) of different sized fragments from the Hays surface soil (Munjor 0-5) at various moisture contents.

Table 1. Effect of moisture content on the ratio log F.C./log wt. of five sizes of fragments from the Hays surface soil, Munjor 0-5 inches.

Screen sizes for separation of fragments	Moisture content (per cent)	Ave. weight of fragments (mg)	Mean crushing force (ounces)	Standard deviation of mean	Mean of logarithms of force to crush	Std. deviation of mean of logs.	$\frac{\log F.C.^{1}}{\log wt.}$ (oz./mg)	Correlation coefficient
	2.06	34.0	37	23	1.49	0.28	0.97	
2.38 mm	3.20	35.9	32	18	1.44	0.27	0.93	-0.95
to 4 mm	6.05	29.8	18	9	1.20	0.23	0.82	
	7.13	32.2	21	12	1.27	0.20	0.84	
	2.03	98.3	82	46	1.84	0.28	0.92	
4 mm to	2.92	82.3	59	30	1.71	0.24	0.89	-0.99
4.76 mm	8.39	94.8	22	10	1.29	0.22	0.65	
	8.48	112.0	30	13	1.44	0.21	0.70	
	1.51	336.6	153	73	2.13	0.24	0.84	
4.76 mm to	2.74	383.5	157	87	2.13	0.26	0.85	
9 mm round	9.40	312.7	62	28	1.75	0.19	0.70	-0.96[3]
	10.39	390.4	39	16	1.56	0.17	0.60	
	13.34[2]	311.8	51	28	1.64		0.66	
	0.59	543.1	198	105	2.22[4]	0.31	0.81	
9 mm rd. to	3.27	550.2	223	114	2.28	0.28	0.83	-0.93
9 mm square	9.37	573.9	84	33	1.89	0.19	0.68	
	11.31	540.2	38	14	1.55	0.17	0.57	
	0.51	922.9	276	83	2.42[4]	0.13	0.82	
9 mm square	2.96	886.2	215	110	2.28	0.24	0.77	-0.99
to 12.7 mm	8.71	1042.7	132	95	2.00	0.13	0.66	
	10.77	898.5	65	26	1.79	0.17	0.61	

1 F.C. stands for the force to crush.

2 Field moisture sample.

3 Correlation coefficient computed without considering field moisture.

4 Part of the fragments in this set had crushing forces of over 400 ounces: all values over 400 ounces were figured at 400 ounces.

and there was sufficient scatter of the standard deviation without transformation.

Collection and Preparation of Soil Samples

Samples Used for Moisture Relationship Study. Four soil samples were used in this study. They will be referred to as Munjor 0-5, Munjor 6-10, Geary 0-7 and Geary 8-14 and represent respectively the surface 0-5 inches and the subsoil 6-10 inches from a winter wheat border on Munjor silty clay loam soil at the Ft. Hays Branch Agricultural Experiment Station and the surface 0-7 inches and the subsoil 8-14 inches of Geary silt loam from the Agronomy Farm of Kansas State College. This latter plot, according to Nijhawan (1947) by whom the samples were taken, "has been under row crops, oats, wheat and alfalfa rotation." Nijhawan describes the sampling as follows:

> These (samples) were taken by means of a spade in four places in the plot and brought to the laboratory in air tight containers. In the laboratory the samples were passed through a one-half-inch mesh screen and thoroughly but gently mixed. . .Before storing the moist sample (in an air tight container), it was allowed to dry a little so that the soil particles should not ball together when stored.

When experimentation was begun, samples studied at field moisture were taken directly from the drums in which the sample had been stored and were sorted according to size by dry sieving. A given number of each size fragment was placed in a covered aluminum can and stored in a humidor. All other fragments were first air dried, sorted according to size by sieving and then adjusted to the desired moisture content. The oven dry samples were heated in an electric oven at 110° C. and then stored in a desiccator. The air dry samples received no treatment after the size separation. The samples in partial equilibrium with saturated air were brought to this condition by storing for two weeks in a humidor. The final set of samples was sprayed by means of an atomizer to bring it to a moisture content above that reached in saturated air and then stored in a humidor for two weeks to approach equilibrium.

Separation according to size was made with sieves of the following sizes: 2.38 mm square, 4.00 mm square, ¼ inch square mesh screen, 9 mm round holes, 9 mm square holes, and ½ inch square mesh screen.

Samples Used in Studying Other Relationships. Material was taken from core samples from the 3 inch, 9 inch and 18 inch levels from 12 different plots at the Ft. Hays Branch Agricultural Experiment Station. Each core was 3 inches in diameter and 4 inches high: thus a core at the 3 inch level included the soil between 1 and 5 inches; a core at the 9 inch level included the soil between 7 and 11 inches; and a core at the 18 inch level included the soil between 16 and 20 inches.

Material from these same cores was used by Olmstead (1947) in collecting data presented in Research Report No. 96: these data formed the basis with which comparison was made in this work. Olmstead said of the original choice of the area for sampling, "The Hays plots were chosen (as versus Colby or Garden City plots) because they have been the least affected by wind and water erosion, and have the best developed soil structure." Most of the plots used in this particular study have continued under the same cropping system for the last 40 years: all were originally broken from buffalo grass sod. The field on which the plots are located is described by Olmstead as follows:

> The slope ranges from nearly level to a maximum of 2 per cent. . . Surface drainage is so arranged that no runoff can enter the plots. . . The soil is tentatively mapped as the Munjor silty clay loam. It is located in a chernozem area but has a slight claypan. The soil survey indicates that the lower and more nearly level Northern part, covering

> about one-fourth of the total area, is slightly different from the remainder of the field. . . The soil of the Hays plots has a very high swelling and shrinkage value.

Core samples were taken from each plot as long after the last major tillage operation as possible; e.g., if a plot was in a rotation in which the land was plowed every three years, sampling was done just before plowing. Samples in the small grains were taken in the stubble after harvest. The cores, when taken, were broken by hand while in the field moisture condition to pass through a one-half-inch- mesh screen, were air dried and stored in waxed, cardboard cartons.

When crushing was begun on these samples, in an attempt to study crushing strength independent of moisture content the Hays core samples were all brought to about the same moisture tension by heating them over night in an electric oven at about 70° C. and storing them in a tight desiccator without desiccant.

RESULTS

Effect of Moisture Content on Crushing Strength

The data presented in Tables 1 and 2 and shown graphically in Figs. 4, 5, 6 and 7 indicate a negative correlation between crushing strength (log F.C./log wt.) and moisture content. This correlation is not only negative, but also linear.

Table 3, taken from Tables 1 and 2, gives in abbreviated form the correlation coefficients between log F.C./log wt. and moisture content for different soils and different size fragments within a given soil. Since each coefficient represents 4 points of comparison, there are 2 degrees of freedom. For there to be significance at the 5% level with 2 degrees of freedom, the correlation coefficient must equal 0.95. A better correlation was found among the medium sized particles than among either the small or the large fragments.

Table 2. Effect of moisture content on the ratio log F.C./log wt. of five sizes of fragments from Munjor silty clay loam 6-10 inches (Hays), Geary silt loam 0-7 inches (Agronomy Farm) and Geary silt loam 8-14 inches (Agronomy Farm).

Soil sample	Screen sizes for separation of fragments	Moisture content (per cent)	Ave. weight of fragments (mg)	Mean of logarithms of force to crush	log F.C.[1] / log wt. (oz./mg)	Correlation coefficient
		2.81	37.4	1.88	1.19	
	2.38 mm	4.24	39.0	1.70	1.07	-0.81
	to 4 mm	9.03	37.6	1.50	0.95	
		10.46	37.3	1.62	1.03	
		2.37	103.2	2.07	1.03	
	4 mm to	3.78	107.2	1.79	0.88	-0.95
	4.76 mm	11.56	115.5	1.54	0.75	
		11.72	125.9	1.45	0.59	
		1.58	260.2	2.15	0.89	
Munjor 6-10"	4.76 mm to	3.60	301.6	2.04	0.82	
	9 mm round	11.85	347.8	1.62	0.64	-0.99[3]
		13.26	312.7	1.41	0.57	
		13.35[2]	260.7	1.90	0.79	
		0.56	576.2	2.25	0.82	
	9 mm rd. to	4.22	538.5	2.08	0.76	-0.99
	9 mm square	12.01	556.9	1.73	0.63	
		14.80	547.3	1.45	0.53	
		0.71	869.5	2.36[4]	0.80	
	9 mm square	4.00	782.0	2.04	0.70	-0.88
	to 12.7 mm	11.84	829.6	1.99	0.68	
		13.59	852.0	1.60	0.55	
		1.89	37.1	1.74	1.11	
	2.38 mm	2.70	50.0	1.53	0.90	-0.73
	to 4 mm	6.39	36.8	1.45	0.92	
		6.46	36.4	1.37	0.88	
		1.89	118.9	1.98	0.96	
	4 mm to	2.59	108.2	1.78	0.88	-0.98
	4.76 mm	7.48	125.0	1.55	0.74	
		8.38	121.8	1.42	0.68	
		0.71	352.7	2.23	0.88	
Geary 0-7"	4.76 mm to	2.56	402.8	2.09	0.80	
	9 mm round	7.70	290.7	1.73	0.70	-0.99[3]
		9.81	373.6	1.56	0.61	
		18.32[2]	270.8	1.47	0.61	
		0.77	648.5	2.35	0.84	
	9 mm rd. to	2.82	561.1	2.35	0.86	-0.96
	9 mm square	8.00	580.9	1.88	0.68	
		9.80	571.3	1.66	0.60	
		0.50	963.8	2.49[4]	0.83	
	9 mm square	2.52	790.8	2.30	0.79	-0.93
	to 12.7 mm	8.29	929.0	2.12	0.71	
		9.69	913.0	1.73	0.58	
		2.91	37.8	1.98	1.25	
	2.38 mm	3.80	32.6	1.81	1.20	-0.88
	to 4 mm	9.65	31.6	1.68	0.97	
		10.05	37.3	1.53	1.12	
		2.18	128.6	2.36	1.12	
	4 mm to	3.60	113.8	2.14	1.04	-0.97
	4.76 mm	10.54	127.2	1.91	0.91	
		12.23	113.2	1.62	0.79	
		1.05	318.0	2.48[4]	0.99	
Geary 8-14"	4.76 mm to	3.31	324.5	2.37	0.94	
	9 mm round	10.90	284.4	1.97	0.80	-0.96[3]
		12.06	234.6	1.61	0.68	
		19.70[2]	238.0	1.72	0.72	
		0.13	559.0	2.54[4]	0.92	
	9 mm rd. to	3.36	548.9	2.50	0.91	-0.96
	9 mm square	11.35	596.9	2.11	0.76	
		13.56	609.0	1.77	0.64	
		0.56	776.8	2.56[4]	0.88	
	9 mm square	3.37	800.9	2.56[4]	0.88	-0.95
	to 12.7 mm	11.00	945.8	2.27	0.76	
		13.44	863.0	1.90	0.65	

1 F.C. stands for the force to crush.
2 Field moisture sample.
3 Correlation coefficient computed without considering field moisture.
4 Part of the fragments in this set had crushing forces of over 400 ounces: all values over 400 ounces were figured at 400 ounces.

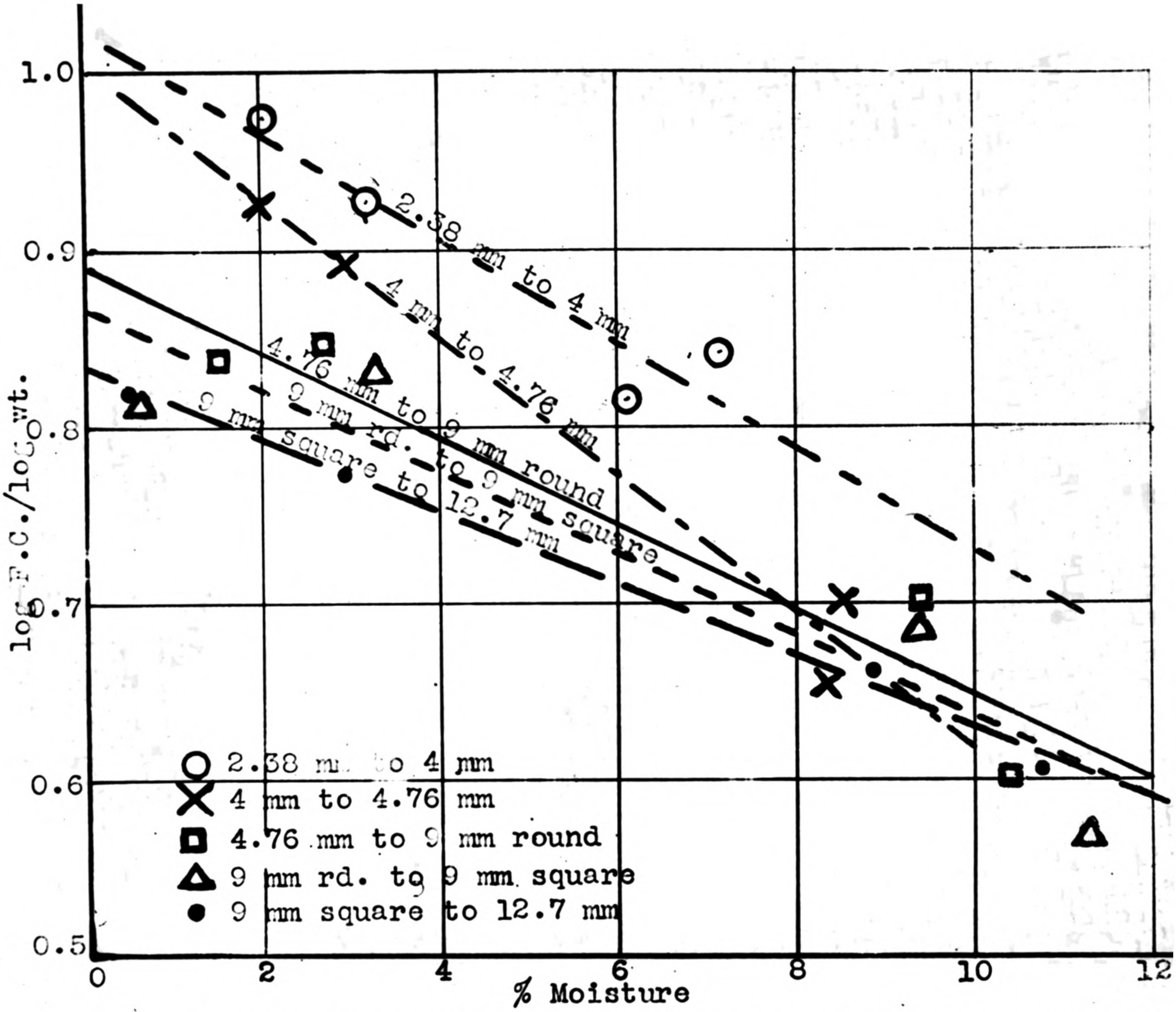


Fig. 4. Effect of moisture content on crushing strength for five sizes of fragments from the Hays surface soil (Munjor 0-5).

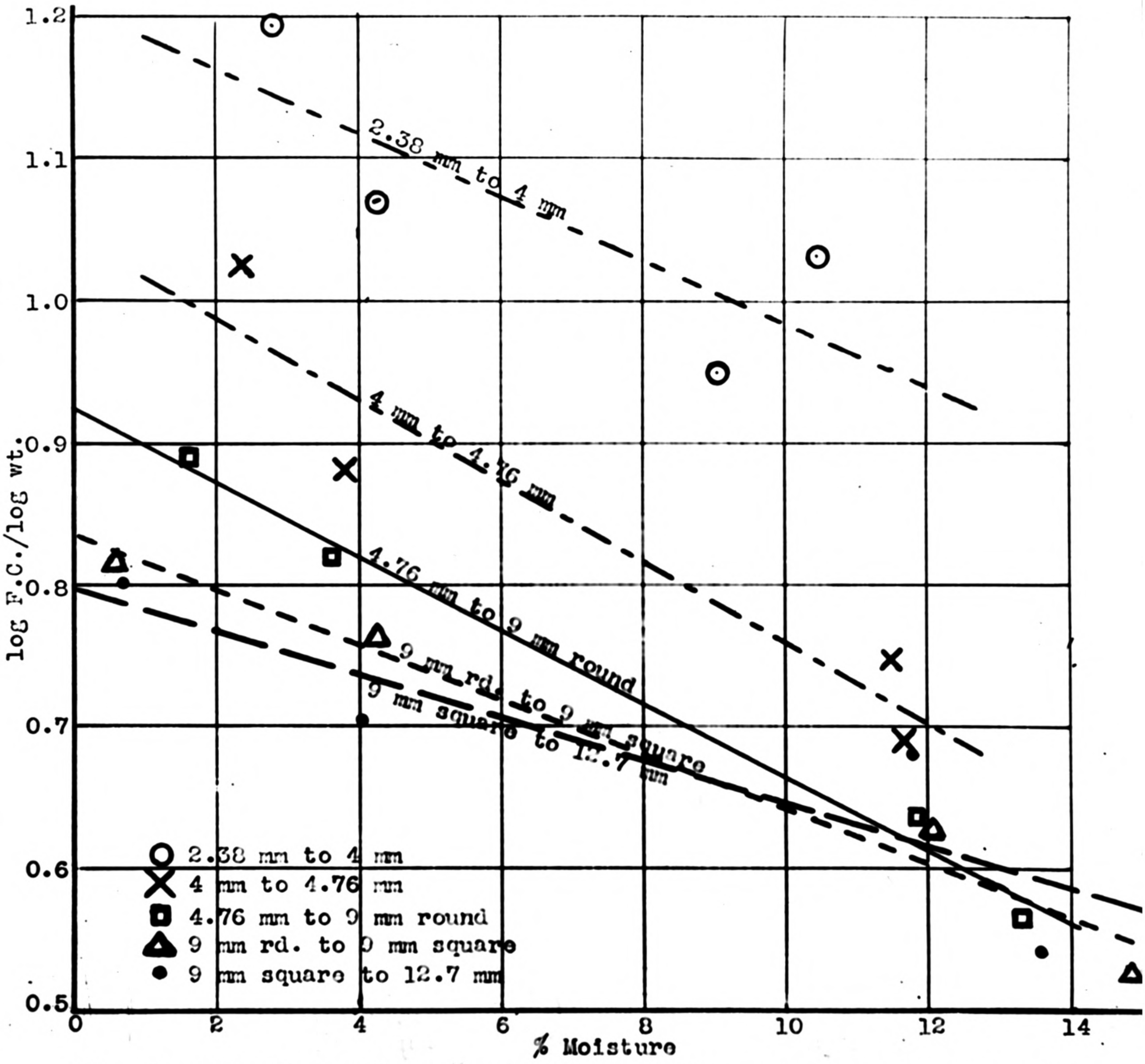


Fig. 5. Effect of moisture content on crushing strength for five sizes of fragments from the Hays subsoil (Munjor 6-10).

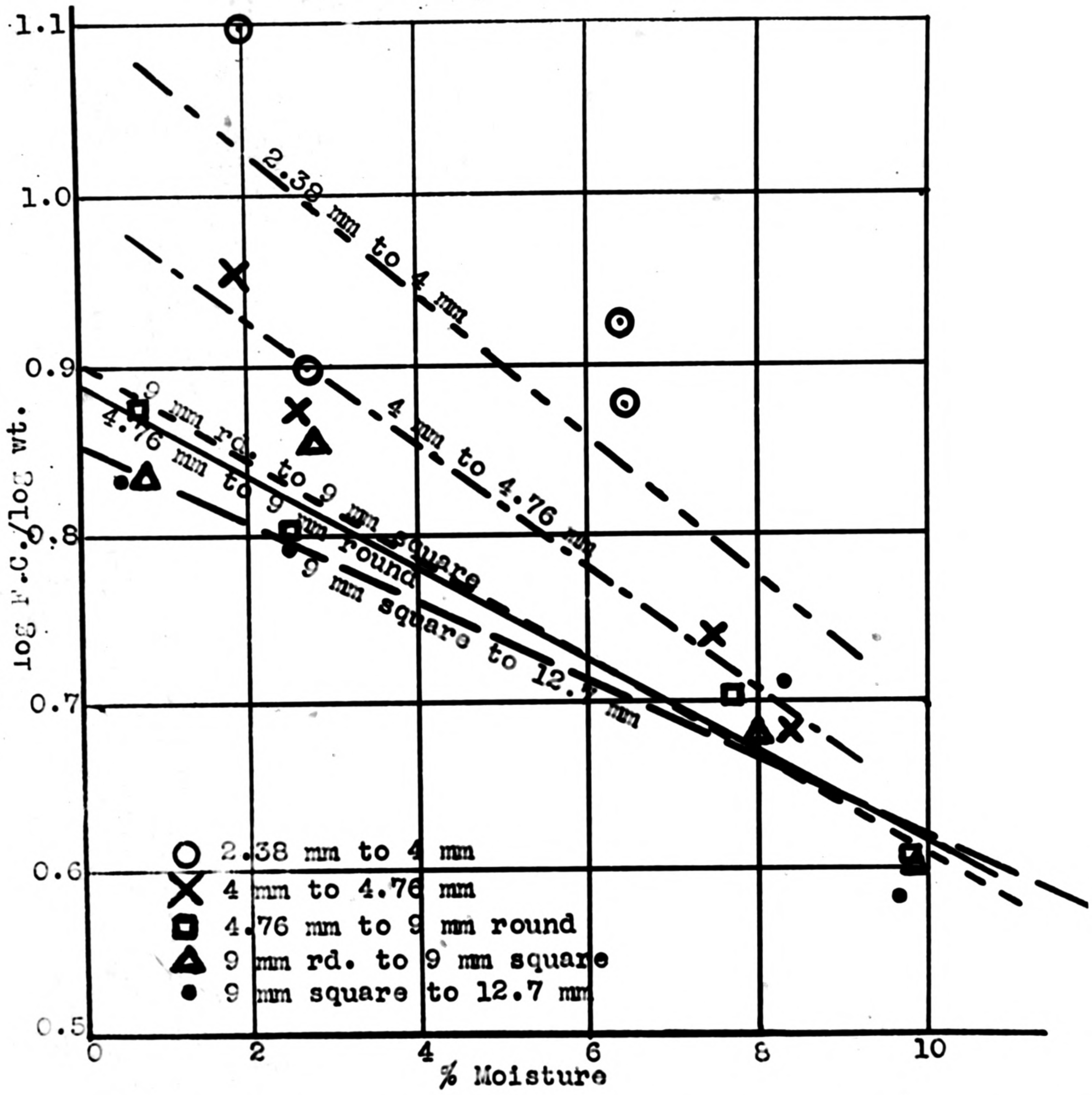


Fig. 6. Effect of moisture content on crushing strength for five sizes of fragments from the Agronomy Farm surface soil (Geary 0-7).

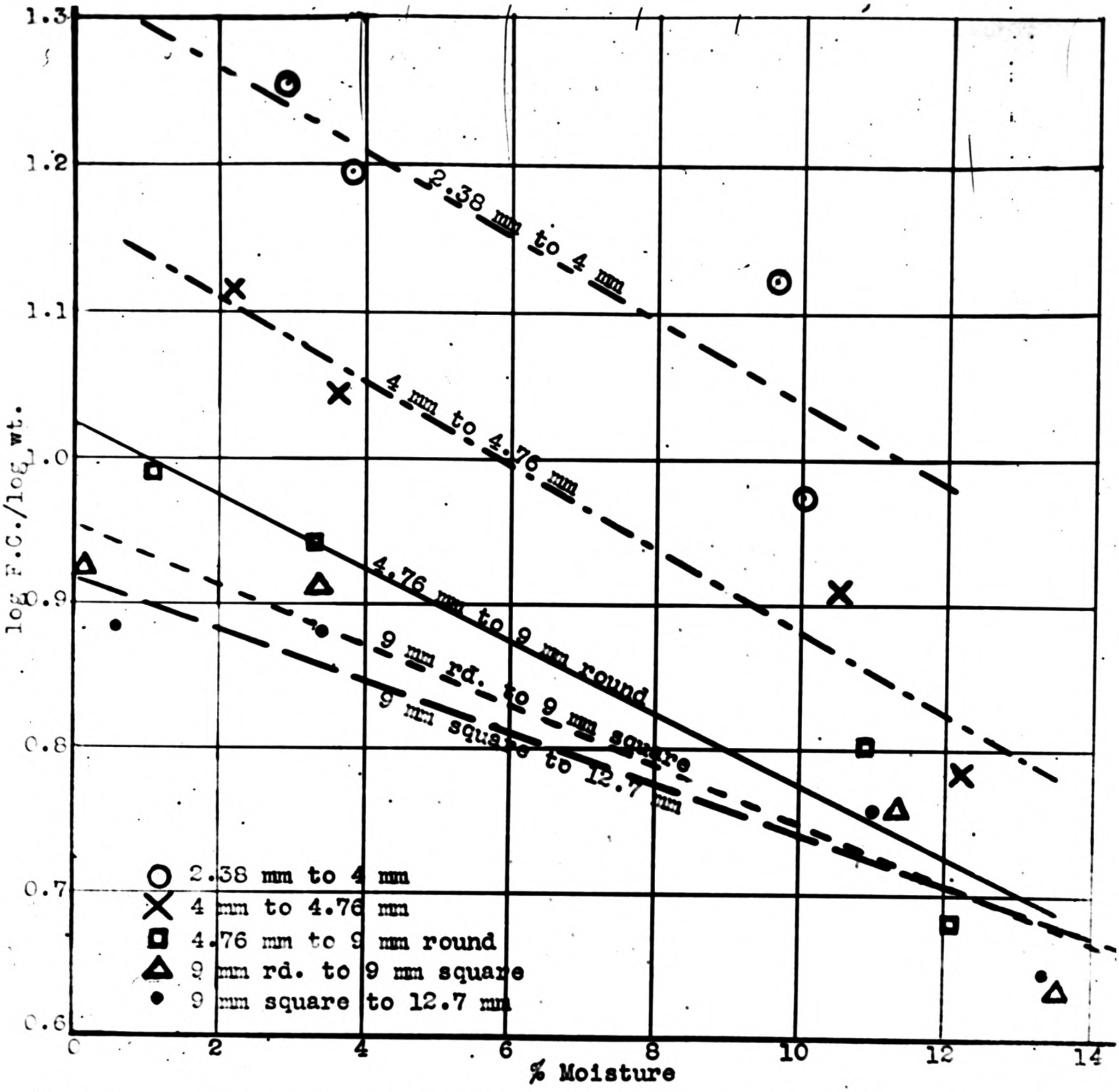


Fig. 7. Effect of moisture content on crushing strength for five sizes of fragments from the Agronomy Farm subsoil (Geary 8-14).

Table 3. Correlation coefficients between log F.C./log wt. and moisture content for five particle sizes from four different soil samples.

Soil sample	Screen size for separation of fragments	Correlation coefficient
Munjor 0-5		-0.95*
Munjor 6-10	2.38 mm to 4 mm	-0.81
Geary 0-7		-0.73
Geary 8-14		-0.86
Munjor 0-5		-0.99*
Munjor 6-10	4 mm to 4.76 mm	-0.95*
Geary 0-7		-0.98*
Geary 8-14		-0.97*
Munjor 0-5		-0.96*
Munjor 6-10	4.76 mm to 9 mm round	-0.99*
Geary 0-7		-0.99*
Geary 8-14		-0.96*
Munjor 0-5		-0.93
Munjor 6-10	9 mm rd. to 9 mm square	-0.99*
Geary 0-7		-0.96*
Geary 8-14		-0.96*
Munjor 0-5		-0.99*
Munjor 6-10	9 mm square to 12.7 mm	-0.88
Geary 0-7		-0.93
Geary 8-14		-0.95

* Significant at the 5% level.

Crushing Strength of the Hays Plot Samples

Effect of Cropping Systems on Crushing Strength. Before comparing crushing strength with other physical properties it seemed advisable to determine whether there were significant differences between plots or whether the variation among the mean crushing strengths of the different plots at any given depth might be due merely to sampling or other error.

The data for this comparison are presented in Table 4 and in Figs. 8 and 9. Figures 8A, 8B and 8C represent respectively the mean crushing strengths at the 18 inch, 9 inch and 3 inch levels for the 12 plots studied. Each point representing a mean crushing strength in this and subsequent portions of this section of the report represents 40 individual crushes; within each plot there were 4 replicates and 10 fragments were crushed from each replicate.

The width of each band in Fig. 8 is three times the standard deviation of the mean on either side of the mean. The common line at each level is the average of the means for that level. If the common line fails to cross all the bands at that level, the chances are less than 1 in 100 that the differences in the mean crushing strengths are due to sampling or other errors.

Relation Between Crushing Strength and Water-Stable Aggregation. A comparison of crushing strength and water-stable aggregation is presented graphically in Fig. 10, data for which are taken from Table 5. In every case the crushing strength increased from the 3 inch level to the 9 inch level and also from the 9 inch level to the 18 inch level. In nearly every case the water-stable aggregation increased from the 3 inch level to the 9 inch level, but decreased from the 9 inch level to the 18 inch level. It is evident from Fig. 10 that no linear relationship existed between crushing strength and water-

Table 4. Crushing strength and standard deviation of the crushing strength for the Hays plots.

Rotation identification	Plot	Cropping system	Mid-depth (inches)	Average weight[1] (mg)	Mean force to crush[2] (ounces)	Crushing strength (oz./mg)	Std. deviation of crushing strength
C-16	12a (south end)	Continuous winter wheat, early fall plow	3	488.0	97.6	0.200	0.019
			9	532.2	210.8	0.396	0.025
			18	589.5	283.0	0.480	0.026
C-16	12b (center of plot)	Continuous winter wheat, early fall plow	3	511.0	108.8	0.213	0.026
			9	553.8	186.1	0.336	0.021
			18	598.6	289.1	0.483	0.022
West border	---	Continuous kafir	3	493.6	126.4	0.256	0.024
			9	528.6	192.9	0.365	0.023
			18	641.4	296.3	0.462	0.022
501	A	Kafir, fallow, winter wheat	3	487.4	159.4[3]	0.327	0.029
			9	570.4	298.3	0.523	0.025
			18	657.6	347.2	0.528	0.018
M.C.	B	Continuous spring oats, fall plow	3	494.1	113.1	0.229	0.020
			9	570.9	225.5	0.395	0.030
			18	608.2	274.9[3]	0.452	0.024
M.C.	B	Continuous spring barley, fall plow	3	562.8	207.1	0.368	0.029
			9	626.1	299.3	0.478	0.022
			18	599.8	339.5	0.566	0.018
Valley	---	Hays buffalo grass, 5 years	3	454.9	130.6	0.287	0.020
			9	486.8	196.2	0.403	0.034
			18	532.5	248.1	0.466	0.030
Valley	---	Field station in Comanche wheat	3	504.0	84.2	0.167	0.015
			9	460.2	156.0	0.339	0.026
			18	518.5	199.1	0.384	0.027
C-15	7	Continuous winter wheat, no tillage, stubble burned	3	502.7	117.1	0.233	0.024
			9	569.1	339.2	0.596	0.018
			18	579.9	355.5	0.613	0.020
C-15	8	Continuous winter wheat, no tillage	3	549.6	152.8	0.278	0.020
			9	625.7	317.2[3]	0.507	0.021
			18	604.1	353.4	0.585	0.014
570	D	Fallow, fallow, fallow, wheat	3	540.5	155.1	0.287	0.026
			9	589.6	258.2	0.438	0.024
			18	639.6	355.6	0.556	0.013
---	---	Permanent pasture	3	457.3	102.0	0.223	0.017
			9	486.0	128.3	0.264	0.023
			18	562.2	240.6	0.428	0.029

[1] Particles are of a size which passes a 3/8 inch square mesh but not a 3/8 inch round mesh.
[2] Average of 40 crushes: 4 replicates with 10 fragments per replicate.
[3] Represents the average of only 39 crushes.

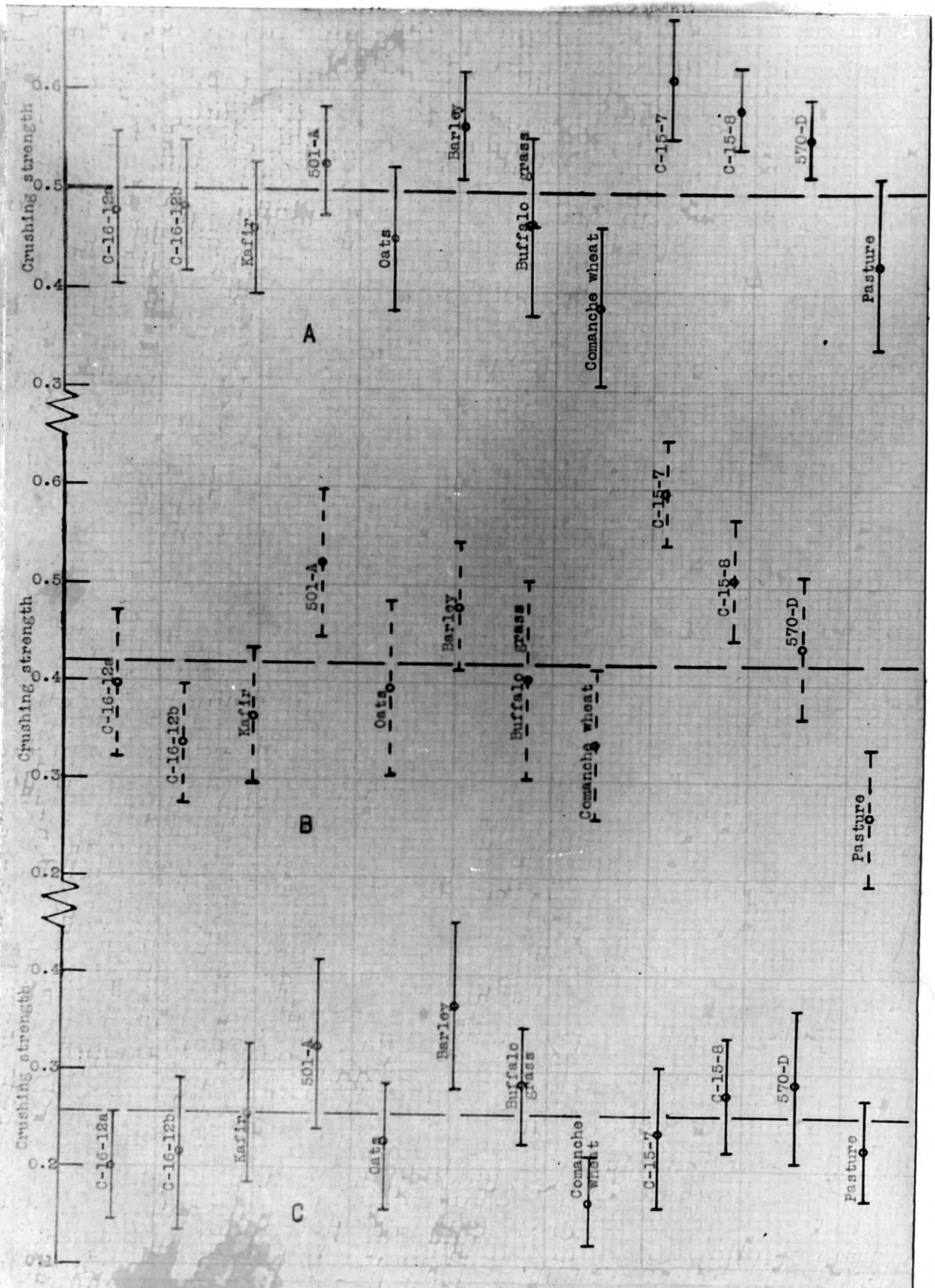


Fig. 8. Mean crushing strength with three times the standard deviation of the mean on either side of the mean for 12 plots from the Hays station, sampled at (A) the 18 inch level, (B) the 9 inch level and (C) the 3 inch level.

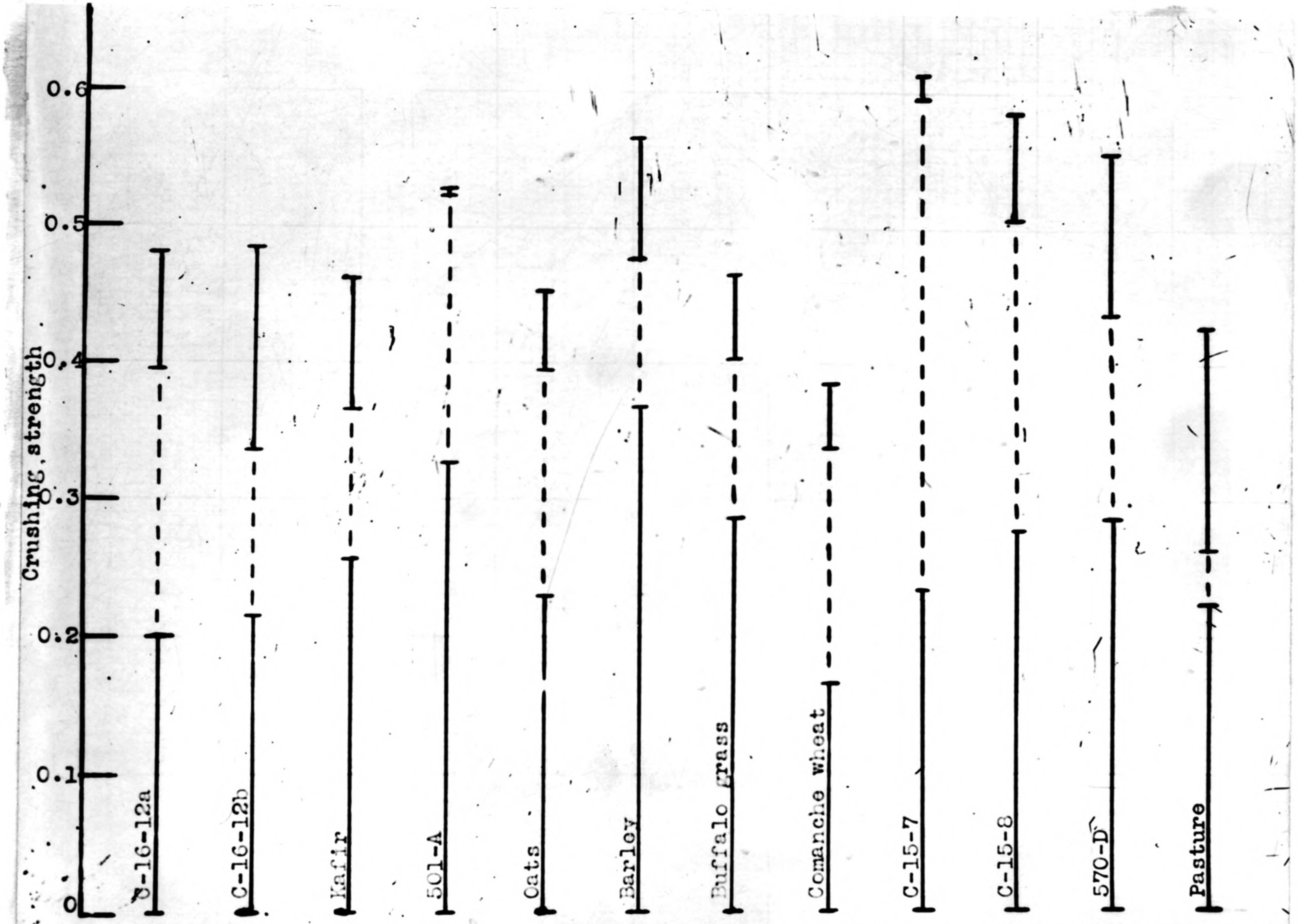


Fig. 9. Mean crushing strengths at the 3 inch, 9 inch and 18 inch levels for 12 plots from the Hays station.

represents:
3 inch level
9 inch level
18 inch level

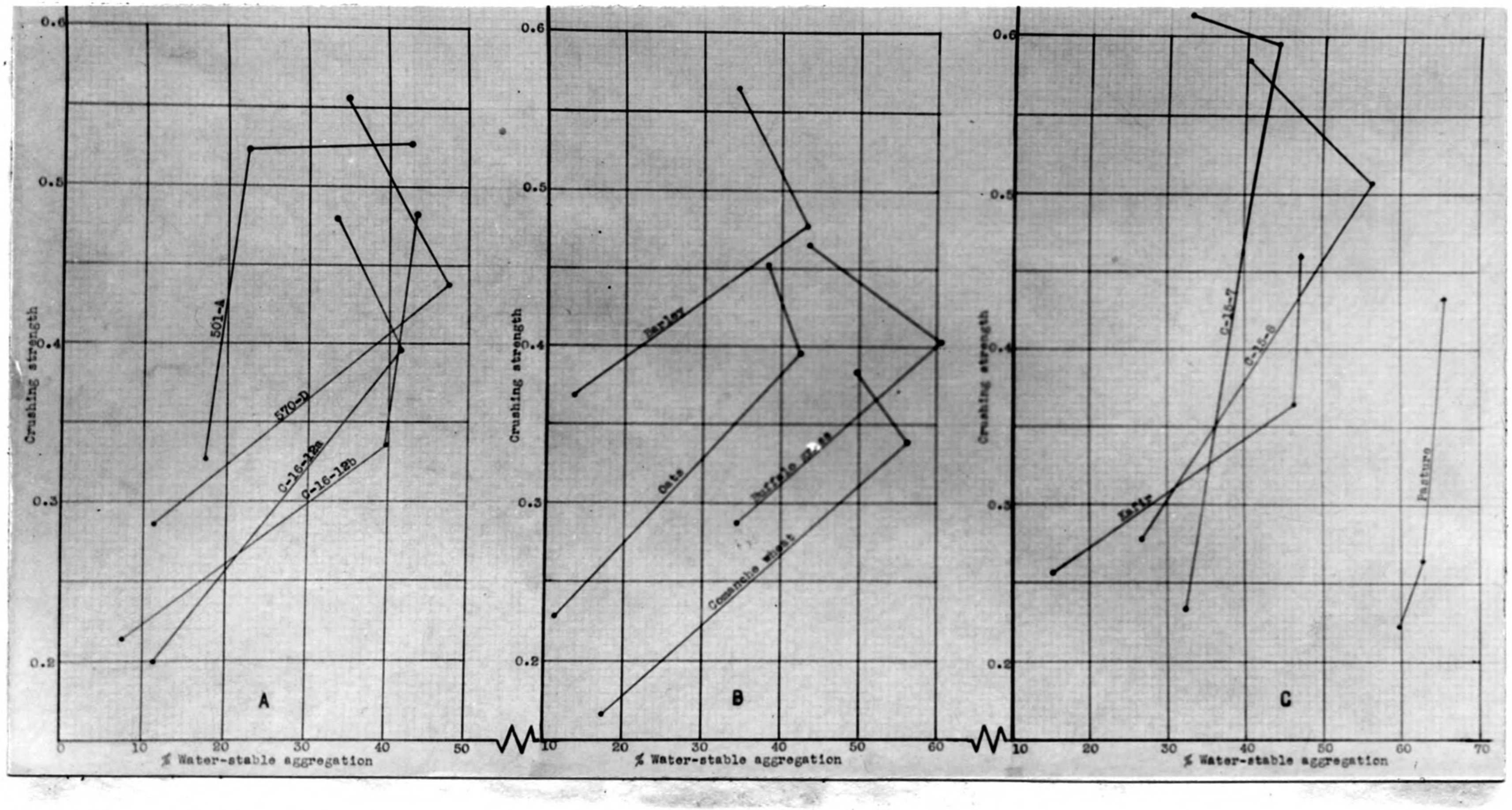


Fig. 10. Relation between crushing strength and water-stable aggregation of the Hays plot samples (A) 501-A, 570-D, C-16-12a and C-16-12b, (B) Barley, Oats, Buffalo grass and Comanche wheat and (C) Kafir, C-15-7, C-15-8 and Pasture.

Table 5. Crushing strength, water-stable aggregation, volume weight and total nitrogen content of soils from Hays plots.

Rotation identification	Plot	Cropping system	Mid-depth (inches)	Water-stable aggregation[1] (per cent)	Volume weight[1] (gm/cc)	Crushing strength (oz./mg)	Nitrogen[2] (per cent)
C-16	12a (south end of plot)	Continuous winter wheat, early fall plow	3	11.7	1.16	0.194	
				17.3		0.293	
				8.8		0.112	
				7.6		0.203	
			9	46.4	1.34	0.426	
				38.2		0.528[3]	
				38.6		0.342	
				43.2		0.288	
			18	35.7	1.46	0.487[3]	
				29.3		0.400[3]	
				34.3		0.604[3]	
				34.7		0.428	
C-16	12b (center of plot)	Continuous winter wheat, early fall plow	3	6.6	1.20	0.216	
				7.9		0.175	
				9.6		0.301	
				6.7		0.161	
			9	36.0	1.36	0.362[3]	
				42.0		0.322	
				42.5		0.290	
				38.6		0.370	
			18	40.7	1.45	0.388	
				43.3		0.610[3]	
				40.4		0.410	
				49.2		0.525[3]	
West border	---	Continuous kafir	3	14.3	1.29	0.194	
				14.4		0.299	
				10.5		0.305	
				22.1		0.228	
			9	40.8	1.39	0.319	
				47.1		0.406	
				52.3		0.345	
				45.9		0.391	
			18	46.1	1.45	0.524[3]	
				52.0		0.473	
				51.1		0.444[3]	
				40.0		0.406[3]	
501	A	Kafir, fallow, winter wheat	3	18.0	1.10	0.302	0.094
				14.1		0.387	
				19.2		0.273	
				18.6		0.346	
			9	25.6	1.20	0.562	
				18.5		0.495	
				24.1		0.507	
				22.1		0.527[3]	
			18	51.8	1.39	0.508	
				46.7		0.448[3]	
				33.2		0.591	
				39.5		0.563	
M.C.	B	Continuous spring oats, fall plow	3	9.9	1.20	0.243	0.124
				10.7		0.182	
				13.1		0.206	
				11.5		0.285	
			9	46.2	1.41	0.350	
				44.2		0.493	
				31.2		0.317[3]	
				47.7		0.420[3]	
			18	37.2	1.52	0.511[3]	
				36.7		0.465[3]	
				38.1		0.467	
				40.6		0.364	
M.C.	B	Continuous spring barley, fall plow	3	14.5	1.24	0.461[3]	0.110
				11.3		0.293	
				16.5		0.377	
				11.9		0.339	
			9	45.5	1.46	0.438[3]	
				40.6		0.366	
				45.7		0.587[3]	
				41.6		0.510[3]	
			18	33.5	1.50	0.528[3]	
				40.4		0.527[3]	
				33.2		0.612[3]	
				29.7		0.599[3]	
Valley	---	Hays buffalo grass, 5 years	3	33.8	1.17	0.268	
				32.9		0.291	
				33.7		0.284	
				36.3		0.306	
			9	54.2	1.24	0.437[3]	
				56.4		0.449[3]	
				62.3		0.329	
				68.9		0.398	
			18	46.9	1.34	0.465	
				35.9		0.476[3]	
				41.9		0.427	
				49.2		0.494	
Valley	---	Field station in Comanche wheat	3	14.2		0.102	
				21.8		0.230	
				20.4		0.172	
				14.1		0.164	
			9	52.6		0.360	
				59.6		0.399[3]	
				58.0		0.286	
				54.1		0.311	
			18	44.3		0.396	
				55.5		0.459[3]	
				48.6		0.355[3]	
				50.6		0.326	
C-15	7	Continuous winter wheat, no tillage, stubble burned	3	35.5		0.127	
				35.4		0.300	
				29.5		0.191	
				28.4		0.314	
			9	46.7		0.586[3]	
				39.3		0.587[3]	
				47.6		0.644[3]	
				42.5		0.567[3]	
			18	33.3		0.614[3]	
				28.5		0.540[3]	
				34.2		0.684[3]	
				35.2		0.613[3]	
C-15	8	Continuous winter wheat, no tillage	3	22.6		0.284	0.155
				27.0		0.313	
				30.1		0.288	
				27.3		0.227	
			9	56.5		0.512[3]	
				53.0		0.510[3]	
				58.1		0.490[3]	
				57.0		0.516[3]	
			18	35.6		0.563[3]	
				41.5		0.596[3]	
				43.6		0.538[3]	
				40.7		0.644[3]	
570	D	Fallow, fallow, fallow, wheat	3	7.6	1.31	0.320[3]	0.122
				20.3		0.397[3]	
				7.5		0.220	
				9.5		0.211	
			9	48.3	1.41	0.344	
				48.3		0.497[3]	
				43.8		0.504[3]	
				48.3		0.405	
			18	34.2	1.50	0.587[3]	
				31.4		0.553[3]	
				35.8		0.535[3]	
				38.2		0.551[3]	
---	---	Permanent pasture	3	57.1	1.20	0.208	0.242
				63.0		0.226	
				60.2		0.273	
				59.5		0.194	
			9	59.1	1.27	0.221	
				65.5		0.256	
				65.0		0.336[3]	
				62.0		0.243	
			18	62.3	1.44	0.366	
				68.7		0.495[3]	
				68.4		0.559[3]	
				63.4		0.290	

[1] Data from Olmstead (1947).
[2] Data from Myers et al. (1943).
[3] Part of the fragments in this set had crushing strengths of over 400 ounces: all values over 400 ounces were figured at 400 ounces.

stable aggregation, nor does there appear to have been any non-linear trend. Thus the research failed to show any correlation between crushing strength and water-stable aggregation.

Relation Between Crushing Strength and Nitrogen Content. Comparison is made with data presented by Myers et al. (1943). Their report includes data on only six of the plots studied in this investigation and since they report on the nitrogen content of only the surface 7 inches, comparison is limited to the surface soil. The comparison is shown in Fig. 11 (data taken from Table 5). The wide scatter of the points indicates that, for the plots studied, there was no correlation between crushing strength and nitrogen content.

Relation Between Crushing Strength and Volume Weight. Volume weight was the only physical property other than moisture content to which crushing strength seemed to be related. The relationship was linear and in all cases the correlation coefficient was significant at the 1% level. The data are presented in Fig. 12 and in Table 5. Each line in Fig. 12 represents 12 values (three depthswith four replicates at each depth), though for simplification in making the graphs the four replicates at each depth were averaged. With 12 points there are 10 degrees of freedom, which means a correlation coefficient of 0.708 is necessary for significance at the 1% level. Table 6 indicates a highly significant correlation between crushing strength and volume weight.

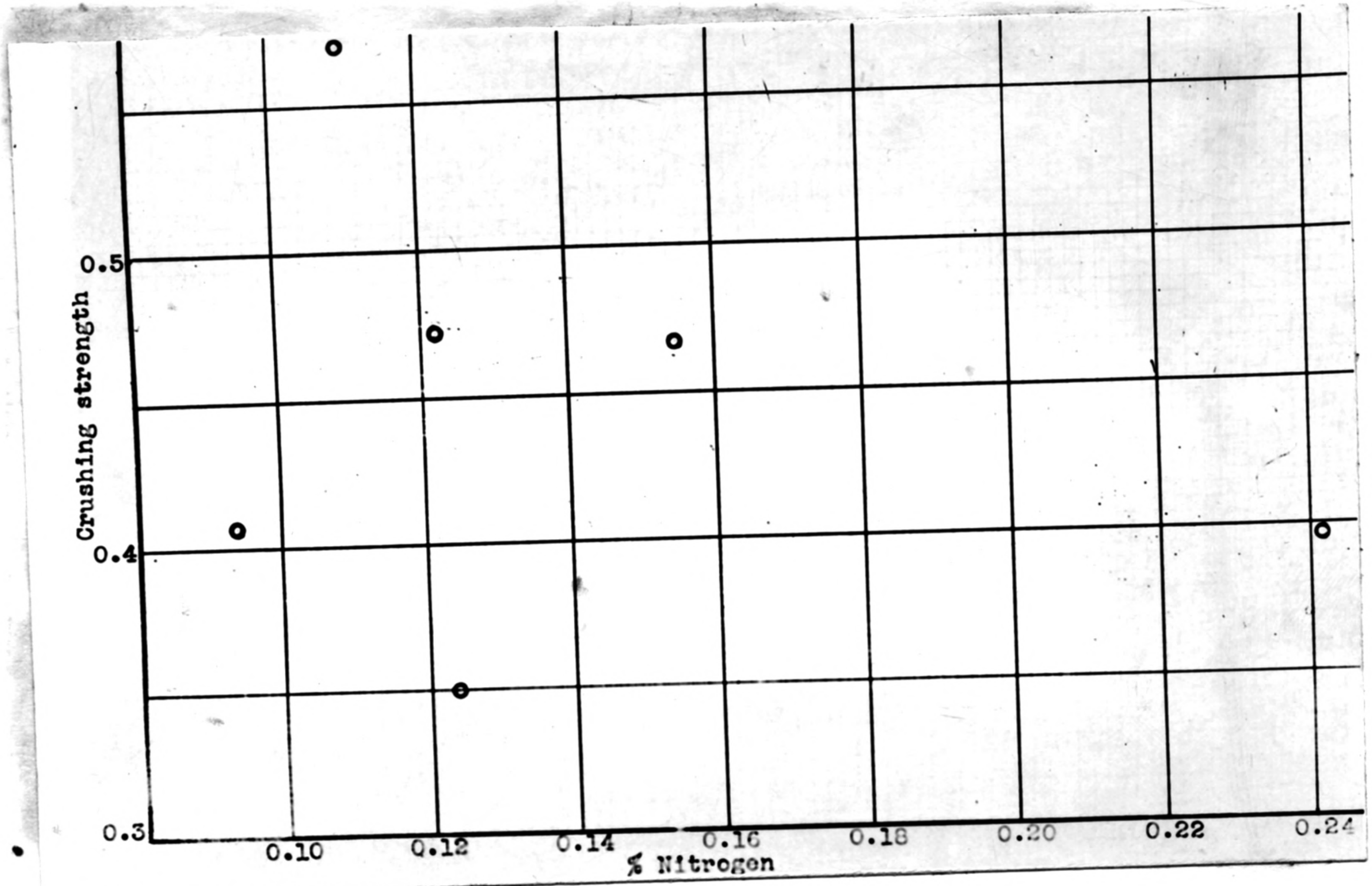
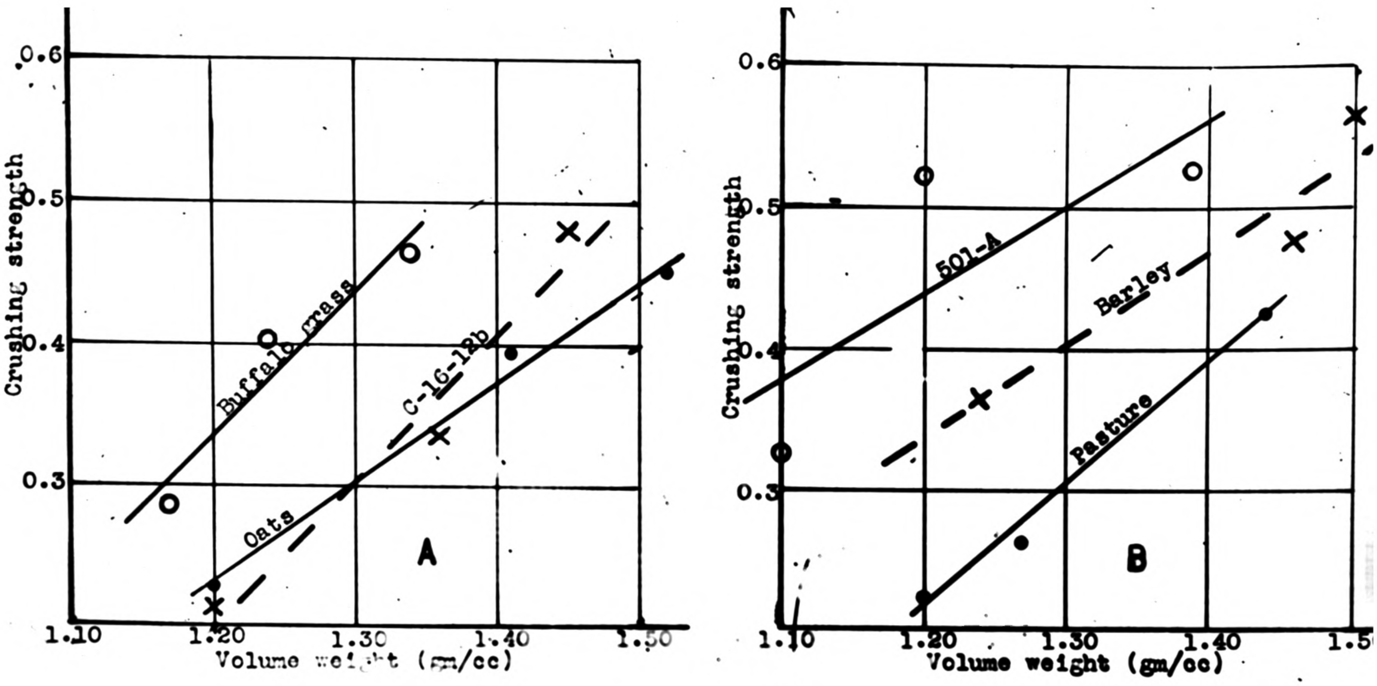


Fig. 11. Relation between crushing strength and total nitrogen content of six soils from the Hays plots.



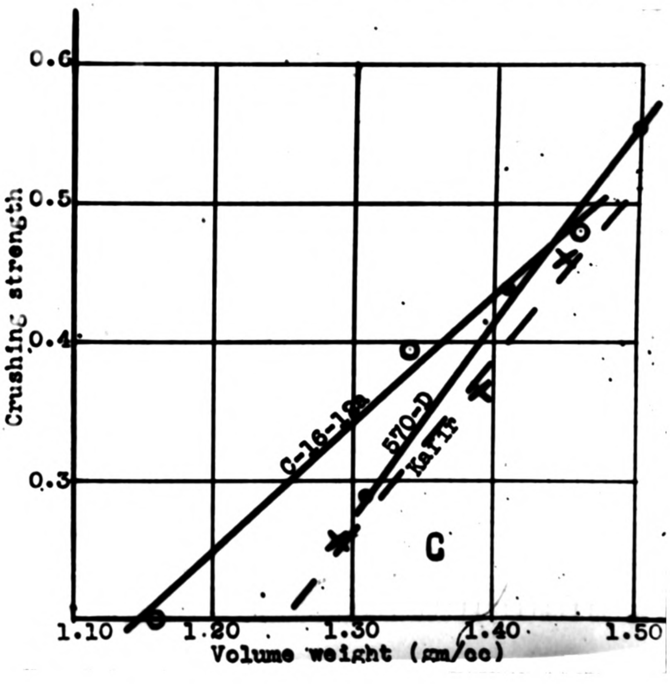


Fig. 12. Relation between crushing strength and volume weight for 12 plots from the Hays station, (A) Buffalo grass, C-16-12b and Oats, (B) 501-A, Barley and Pasture and (C) C-16-12a, 570-D and Kafir.

Table 6. Correlation coefficients for crushing strength and volume weight for nine plots at the Ft. Hays Experiment Station.

Plot or rotation	Mid-depth (inches)	Crushing strength (oz./mg)	Volume weight (gm/cc)	Correlation coefficient
	3	0.20	1.16	
C-16-12a	9	0.40	1.34	0.83
	18	0.48	1.46	
	3	0.21	1.20	
C-16-12b	9	0.34	1.36	0.85
	18	0.48	1.45	
	3	0.26	1.29	
Kafir	9	0.37	1.39	0.89
	18	0.46	1.45	
	3	0.22	1.20	
Pasture	9	0.26	1.27	0.79
	18	0.43	1.44	
	3	0.23	1.20	
Oats	9	0.40	1.41	0.86
	18	0.45	1.52	
	3	0.37	1.24	
Barley	9	0.48	1.46	0.73
	18	0.57	1.50	
	3	0.29	1.31	
570-D	9	0.44	1.41	0.87
	18	0.56	1.50	
	3	0.33	1.10	
501-A	9	0.52	1.20	0.71
	18	0.53	1.39	
	3	0.29	1.17	
Buffalo	9	0.40	1.24	0.89
grass	18	0.47	1.34	

DISCUSSION

Effect of Moisture Content on Crushing Strength

At the time the data were taken, five moisture contents were used. Only four moisture contents were considered, however, in preparing Figs. 4, 5, 6 and 7 and in computing the values in Table 2. The moisture level which was deleted was that of field moisture. The reason for this omission is shown in Fig. 13, data for which are found in Tables 1 and 3. In each case samples at field moisture had a higher crushing strength than other samples of about the same moisture content or, in other words, the field moisture point does not lie close to the curve.

This matter was not investigated further but it is believed that this discrepancy is due to the fact that the samples crushed at field moisture had reached a state of equilibrium with regard to moisture distribution which imparted a more stable structure. The samples at the other moisture contents, on the other hand, were all brought to an air dry state first and then adjusted to their respective moisture levels. The maximum time for this adjustment was two weeks. Olmstead (1937) found that the soil in a tube 18 inches long filled with moist soil in one half, dry soil in the other half, and then sealed, failed to reach a state of equal distribution of the moisture in a year. Thus in the present study equilibrium was merely approached but not reached and the investigation was thereby limited. Having a higher moisture content at the surface than in the center of the fragments appears to effectively lower the crushing strength: in converse to this, the field moisture samples may have been somewhat drier on the surface than in the center, giving an effectively higher crushing strength.

Since the four moisture levels used represented in each case samples

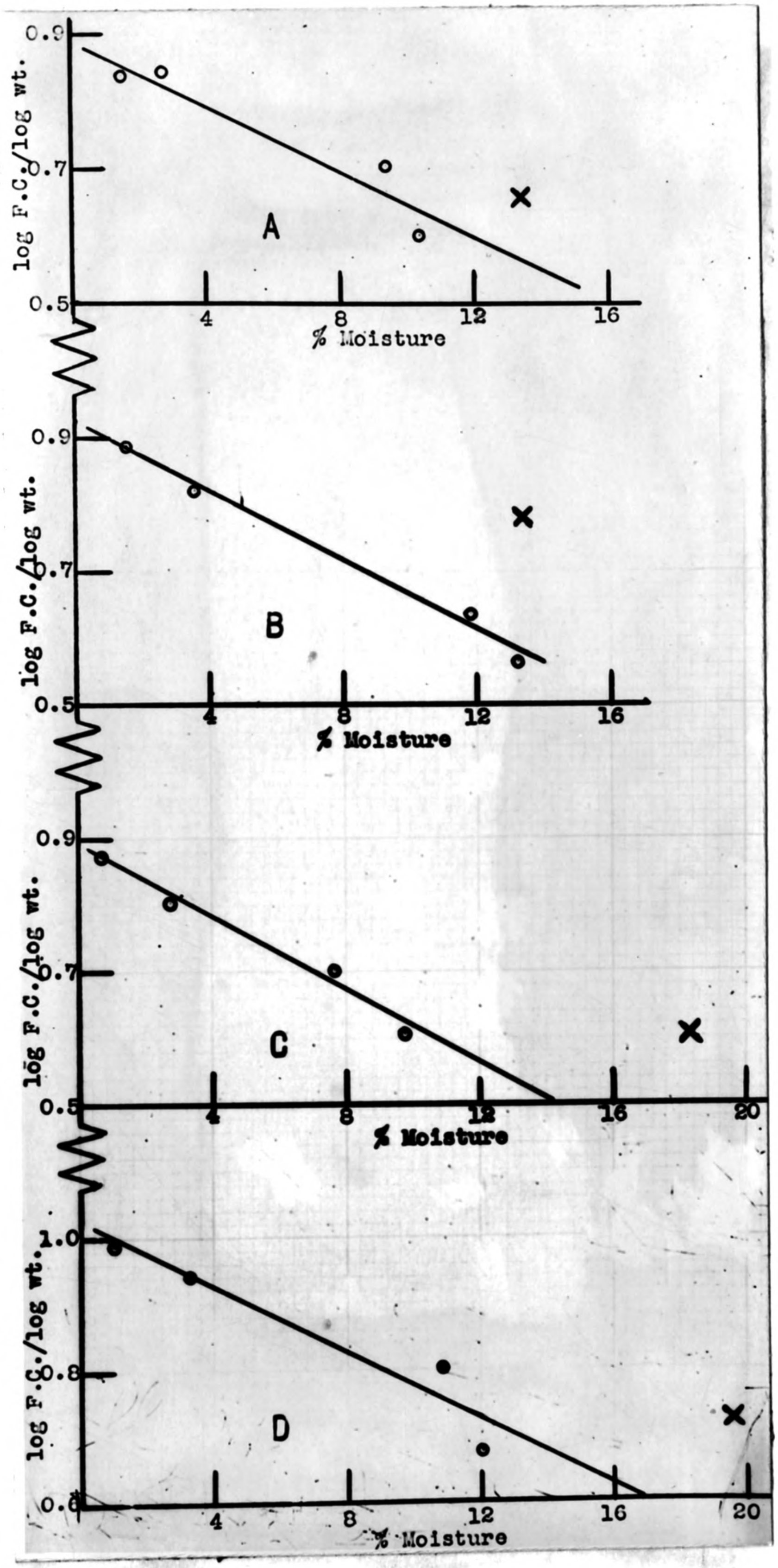


Fig. 13. Relation between crushing strength and moisture content at five moisture levels, including field moisture (X), for particles of the sieve separation 4.76 mm square to 9 mm round from (A) Munjor silty clay loam 0-5 inches (Hays), (B) Munjor silty clay loam 6-10 inches (Hays), (C) Geary silt loam 0-7 inches (Agronomy Farm) and (D) Geary silt loam 8-14 inches (Agronomy Farm).

brought to an air dry condition and then adjusted over the same period of time to a state approaching equilibrium, it was considered that the correlation of moisture content and crushing strength was valid. It should be pointed out, however, that the data are limited in not including moisture studies in the range between air dry samples and those stored in saturated air. It is possible that inclusion of such data might not confirm the linear relationship. Hardesty and Ross (1938) found the same relationship between moisture content and crushing strength for fertilizer pellets which this study showed for soil fragments. The moisture range which they studied was from 0 to 5.28 per cent.

While it was not the purpose of this investigation to study binding forces in aggregates, it might be noted that the general relationship between moisture content and crushing strength found in this study is in agreement with Russell's (1935) dipole-cation-dipole linkage theory which states that as the dipole units (water molecules) are removed by evaporation (or freezing) the bonds between the clay particles and cations are shortened and strengthened.

Crushing Strength of the Hays Plot Samples

<u>Effect of Cropping Systems on Crushing Strength</u>. A description of the cropping systems on the 12 plots used in this part of the study is found in Table 5. It was shown (p. 20) that there were significant differences in the crushing strengths of the different plots at the different levels, but the question remains as to whether these differences can be attributed to the cropping systems or whether they are unrelated to the treatment the plot has received. In order to visualize the variations from plot to plot and within plots, the mean crushing strength at the 3 inch, 9 inch and 18 inch levels

for each plot are shown in Fig. 9. Figure 9 is a composite of parts A, B and C of Fig. 8.

It was found on every plot that the crushing strength increased with depth of sampling. This may be in line with the findings of Hardesty and Ross (1938) regarding the influence of the size of primary particles on the hardness of the aggregates formed from them. They found that the smaller the primary particles the harder was the aggregate. Elutriation of clay particles from the surface soil to subsoil would bring about a decrease of the smaller particles in the surface soil and an increase of them in the subsoil, which might be expected to cause a harder subsoil. It is questionable whether this factor is very important in the present work, however, for while there is slightly less clay in the surface foot of soil than in the second foot, mechanical analysis (Middleton, Slater and Byers, 1932) of typical plots shows very little difference in the clay content at various depths.

Certain things which show up in Fig. 9 might be more or less expected. It would seem logical that the surface soil of plot 501-A should have a high crushing strength for this plot was plowed 14 inches deep every three years which would bring much of the hard subsoil to the surface. By the same line of reasoning, however, the crushing strength at the 9 inch level should be much the same as that at the 3 inch level. Instead, it was found to be almost the same as at the 18 inch level.

If cropping systems have any direct relationship to crushing strength, then the lines in Fig. 9 representing oats and barley, which are adjoining plots, should be quite similar, for both are spring cereal grains and practically the same tillage practices are used for both. It is seen, however, that the oats plot is much more like the buffalo grass or kafir plots, as far as crushing strengths are concerned, than it is like the barley plot.

Comparison might also be made between the two wheat plots, C-15-7 and C-15-8, and the pasture plot. The two wheat plots were drilled in the stubble without there having been any other tillage. Thus none of the three plots had been disturbed below the top two inches or so. The virgin pasture showed the least difference in crushing strength in going from the 3 inch level to the 9 inch level while the two plots, C-15-7 and C-15-8, showed the greatest differences of any of the plots in going from the 3 inch to the 9 inch level.

Thus while there are significant differences between plots these differences in crushing strength do not appear to be correlated with cropping systems. Neither do they appear to be due to seasonal differences at the time of sampling, for, with the exception of Hays buffalo grass, Comanche wheat and the permanent pasture, all plots were sampled in the fall of 1944. Within the period required for taking samples there were some variations in moisture content,and moisture content at the time of sampling, for which no records are available, may be a factor influencing crushing strength.

Effect of Nitrogen Content on Crushing Strength. It might be supposed that soils high in nitrogen or organic matter (nitrogen being an index of organic matter) would form softer fragments than soils low in nitrogen. On the other hand, organic matter is considered to act as a binding agent in soils and should perhaps lead to higher crushing strengths. Only six values were available for comparison and, as seen in Fig. 11, these points are quite scattered, indicating no correlation between crushing strength and nitrogen content. Baver (1935) studied the effect of organic matter and clay content on aggregation and found a direct correlation for each factor, but "if the various soils are grouped according to their clay contents it is seen that the effect of organic matter is more pronounced with those soils containing the smaller amounts of clay." Thus, even if it were assumed that an effect known to influence aggregation would also have a direct relationship to crushing strength, it is probable that nitrogen levels were so low that any effect which organic matter might have on crushing strength would be masked by other factors.

Effect of Volume Weight on Crushing Strength. As was shown in Table 6, there is a highly significant linear correlation between crushing strength and volume weight. This means that, at least for the range of densities which these soil samples included, the denser a soil is the harder or more resistant to crushing are fragments of that soil, but the question remains as to which factors influence the packing or density of these dry land soils.

It might be noted that in the same measure that no relationship was established between crushing strength and cropping systems by this investigation neither was any relationship between volume weights and cropping systems reported by Olmstead (1947).

SUMMARY

This study was undertaken in order to evaluate the applications and limitations of a technique for measuring one of the physical properties of the soil which has, until now, received little attention, namely, the crushing strength of fragmented soil material.

It was desired to know whether this property was influenced by cropping systems and could be used to distinguish between soils of the same type which have been under different cropping systems. It was desired also to know whether the crushing strength was related to other properties of the soil such as moisture content, water-stable aggregation, nitrogen content and volume weight.

Crushing was accomplished by means of a plunger, which, operated by a

rack and pinion, pressed upon a platform mounted on a pair of ordinary household scales. Moisture adjustments were accomplished by oven drying and storing in desiccators; storing in humidors; and spraying with an atomizer and then storing in a humidor. Crushing of fragments with higher moisture content than air dry was conducted in a cubicle in which humidity was maintained at nearly 100 per cent. The soil for all studies other than moisture relations was the Munjor silty clay loam from the Ft. Hays Branch Agricultural Experiment Station.

It was found that while there were significant differences in the crushing strengths among plots under different cropping systems, these differences do not appear to be related to the treatment the soil has received, for some plots under very similar treatment had significantly different crushing strengths while other plots under quite different treatments did not have significantly different crushing strengths.

A significant negative correlation was found to exist between crushing strength and moisture content. This was true of both surface soils and subsoils from Hays, Kansas, and from Manhattan, Kansas.

No relationship was found to exist between crushing strength and water-stable aggregation or between crushing strength and nitrogen content.

A highly significant correlation was found to exist between crushing strength and volume weight, indicating that the density of the fragments is the main factor (moisture content being held constant) contributing to the hardness of the fragments.

It may be that such factors as cementing agents (which influence water-stable aggregation, for example) have some effect on crushing strength, but within the limitations of the experiment volume weight and moisture content effectively masked any other influence which may exist.

ACKNOWLEDGMENTS

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