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Aggregate Tensile Strength and Friability Characteristics of Furrow and Sprinkler Irrigated Fields in Southern Idaho

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Agricultural crops grown in southern Idaho are furrow or sprinkler irrigated. Therefore, the soil experiences several wetting and drying cycles each growing season that can contribute to changes in aggregate tensile strength and friability. The objective of the research was to evaluate the influence of irrigation on soil structural properties. Four furrow-irrigated fields were sampled at the top and bottom of the field, in the furrow and on the bed location of the furrow. Five sprinkler-irrigated fields were sampled at depths of 0–5 and 5–15 cm and at the top and bottom of the field. Results from this study indicate that differences in tensile strength in furrow-irrigated fields were only evident soon after irrigation; otherwise, there were few differences in tensile strength and friability. In sprinkler-irrigated fields tensile strength increased with depth in three of the five fields measured. Friability was less affected by depth.

Keywords Soil structure, soil tilth, tensile strength

Introduction

In agricultural systems establishment and growth of crops relies on soil structural properties, soil tilth, and “ease of tillage.” Tensile strength is considered one of the most useful indicators of soil structural condition and is defined as the stress, or force per unit area, required to cause soil to fail under tension and provides information on the ability of roots to penetrate the soil (Imhoff, Pires Da Silva, and Dexter 2002). The heterogeneity of tensile strength that results from the presence of microcracks or other flaws within the soil aggregates has been defined as friability (Watts and Dexter 1998). Friability represents the tendency for a mass of unconfined soil to break down and crumble under an applied stress into a particular range of fragments and relates to soil tilth and tillage (Macks et al. 1996). A friable soil requires minimum tillage to produce a good seedbed of small aggregates, providing optimum conditions for plant growth. A nonfriable soil may have a high-energy

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requirement for tillage and produce a poor seedbed with large clods and aggregates, thus providing unsuitable conditions for germination, emergence, and establishment of plants.

Agricultural fields in southern Idaho are both furrow and sprinkler irrigated. Furrow-irrigated fields wet rapidly as water flows down the furrow, remain saturated for several hours during irrigation, and then dry for several days or weeks depending on irrigation schedules. Sprinkler-irrigated fields generally become wet more slowly and are irrigated at more frequent intervals. These wetting and drying cycles affect the soil structure by causing slaking that leads to a progressive decline in aggregate strength (Gardner, Laryea, and Unger 1999). Drop impact from sprinkler irrigation breaks down surface aggregates, compacts the surface layer, and washes fine particles into pores below the surface, causing structural seals can greatly overshadow other factors affecting infiltration on unprotected soils (Segeren and Trout 1991).

Several devices have been designed to measure aggregate tensile strength over the years. Dexter and Kroesbergen (1985) described an apparatus that measured the load applied to the poles of an aggregate positioned between two flat, parallel metal plates. Depending upon the sample aggregate's size and suspected strength, the load was measured with (1) an analog balance, (2) the progressive loading, by hand, of a lever, or (3) a proving ring-type loading ring, similar to that of Rogowski, Moldenhauer, and Kirkham (1968), that had a dial gauge to record the maximum load applied. Unfortunately, none of these devices automatically recorded or logged the progressively increasing load applied to the aggregate until it failed. Dexter and Kroesbergen (1985) did note, however, that their small-aggregate apparatus could be improved using a digital rather than analog balance that would output its reading to a data logger or computer. In this study, a device was custom designed to interface with computer hardware and software so the load applied could be read automatically. This device was used to study the impact of sprinkler and furrow irrigation on soil structure, by measuring aggregate tensile strength and friability.

Materials and Methods

Hardware and software systems were developed to automate the process of crushing soil aggregates to calculate aggregate tensile strength and friability. The system hardware included a steel loading frame, an integrated programmable motion controller (Intelligent Motion Systems, Marlborough, Conn.), and motor driver (IMS MX-CS100-401) with a computer-controlled stepper motor (12-V 87 H4C, Hayden Kerk Motion Systems, Waterbury, Conn.) (Figure 1). The stepping motor applied a constant strain at a rate of 0.27 mm s^{-1} until the aggregate completely failed. A load cell (Transducer Techniques, Temecula, Calif.) was attached to the stepping motor and the voltage was recorded via an analog-to-digital converter (USB-1608FS, Measurement Company Corp., Norton, Mass.) interfaced to a PC through a USB port (Figure 1). The flat tip of a hand-held penetrometer was attached to an adapter on the load cell. The tip can be modified depending on the desired use of the instrument. The load cell was calibrated using the shunt calibration method and the information from the manufacturer's calibration certificate (Transducer Techniques, Temecula, Calif.).

A Visual Basic program was written to read and plot the digitized voltages in real time, storing data for each aggregate in a user-specified ASCII file. The aggregate strength crusher was programmed to stop when the maximum voltage load for the load cell was reached as this protected the load cell from becoming damaged if the aggregate contained a rock or other hard substance. In this study, approximately 3720 aggregates were tested and the program effectively stopped whenever the maximum voltage for the load cell was

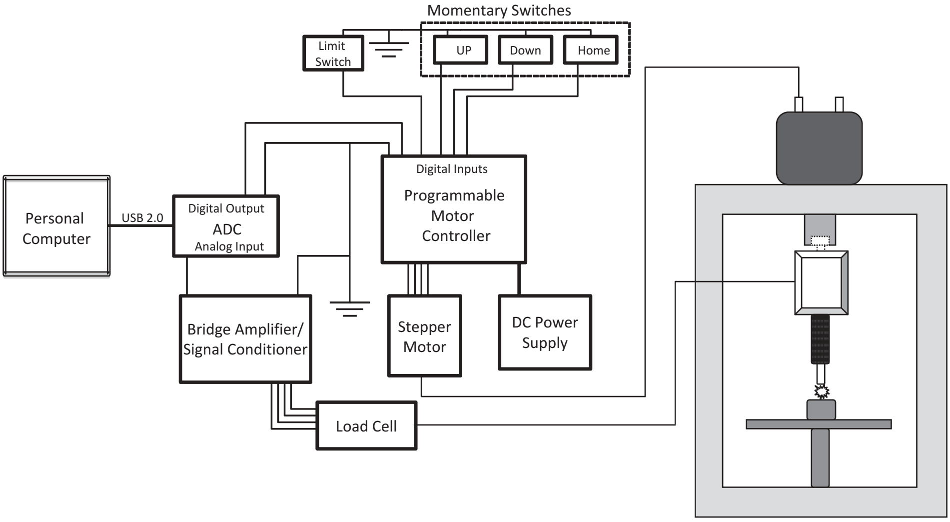

Figure 1. Aggregate strength crushing apparatus with schematic of the circuit diagram.

exceeded, as happened when the aggregate was actually a small pebble or contained a rock fragment.

An Excel macro was written to process the data so each data record had the treatment, replication, aggregate weight, and other necessary information for data analyses. The maximum voltage was calculated from the data for each aggregate using Proc Means (SAS Institute, Cary, N.C., USA). The maximum voltage was used to calculate the force applied to the aggregate at the point of fracture using the load cell calibration.

Aggregate strength was measured on aggregates collected from nine irrigated fields in southern Idaho. Samples were collected from the inflow end (top) and the outflow end (bottom) of furrow-irrigated fields. On sprinkler-irrigated fields, samples were collected from areas that were the top and bottom of the field when it was previously furrow irrigated and from two depths (0 to 5 cm and 5 to 15 cm). The furrow-irrigated fields were further separated into the bed (area between furrows) and furrow (area where water flows) areas. The soil samples were stored at 4 °C until they were sieved. All nine fields had silt loam soils (Table 1). The soils are all described as very friable in the top horizon to friable in the second horizon (https://soilseries.sc.egov.usada.gov). The crop, irrigation, and cultivation practices are listed in Table 1.

The soil samples were sieved so aggregates in the size class 4.0 to 6.35 mm remained in the sieve and were oven dried at 105 °C for 24 h. After removal from the oven, aggregates were placed in a desiccator containing dry silica gel until tensile strength measurements were made. Oven-dried aggregates were used to eliminate the effects of aggregate water content on crushing forces. Dexter and Kroesbergen (1985) consider the oven-dried state a standard reproducible condition and they do not recommend measurement of air-dried aggregates because small differences in aggregate water content can have a significant effect on tensile strength. Thirty-five individual aggregates were crushed until the aggregate completely failed (3720 total aggregates for this study). Each aggregate was weighed before crushing to calculate the diameter using method 4 (Dexter and Kroesbergen 1985) as follows:

$$d = (m/\overline{m}_i)^{1/3}$$

Table 1
Description of irrigation and soil types for the soil samples from fields in southern Idaho

Field	Irrigation type	Soil type	Tillage	Crop	Other notes
1	Furrow	Sluka Silt loam	No tillage since harvest, straw removed	Barley	Irrigated bottom half of field (east) within a week; irrigation in top half of field was in progress. Bottom samples and sample 1 on top were irrigated. Samples 2 and 3 on top were not irrigated.
2	Center pivot	Portneuf silt loam	Disked	Barley	Irrigated after harvest; field was moist but not wet. Volunteer barley was 6 inches tall.
3	Furrow	Sluka silt loam	No data	Barley	Irrigated within 2 weeks.
4	Center pivot	Portneuf silt loam	No tillage after harvest	Grain	Irrigated after harvest.
5	Furrow	Portneuf silt loam	Straw removed	Grain	Not irrigated after harvest. Soil dry and hard.
6	Center pivot	Portneuf silt loam	Disked, straw removed	Barley	Irrigated after harvest; volunteer barley was 4 inches tall.
7	Furrow	Portneuf silt loam	No tillage, straw removed.	Barley	Field had not been irrigated after harvest; dry and very hard.
8	Wheel line	Portneuf silt loam	No tillage, straw removed.	Barley	Irrigated approximately 2 weeks before sampling.
9	Center pivot	Chiara silt loam	No tillage	Beans	No data

Table 2
Friability (Fr) soil classification for the coefficient of variation method (Imhoff et al. 2002)

Parameter	Soil classes
$Fr < 0.10$	Not friable
$Fr = 0.10–0.20$	Slightly friable
$Fr = 0.20–0.50$	Friable
$Fr = 0.50–0.80$	Very friable
$Fr > 0.80$	Mechanically unstable

where m is mass of the individual aggregate and $\overline{m}_i$ is mean mass of the ith class. Aggregate tensile strength was calculated as

$$Y = a\left(\frac{F}{d^2}\right)$$

where $a = 0.576$, the proportionality constant (Imhoff, Pires Da Silva, and Dexter 2002), d is the diameter of aggregate, and F is the force at failure. The compressive force at failure, F, is calculated as $F = b\ g$, where b is the load (kg) calculated from the load cell output and g is the acceleration due to gravity (9.807 m s^{-2}) (Dexter and Kroesbergen 1985).

Friability, Fr, defined as the tendency of a mass of unconfined soil to disintegrate and crumble under an applied stress, can be calculated from tensile strength using the coefficient of variation method as follows:

$$Fr = \frac{\sigma_Y}{\mathrm{Y}} \pm \frac{\sigma_Y}{\mathrm{Y}\sqrt{2n}}$$

where σ_Y is the standard deviation of measured values of tensile strength, Y is the mean of the tensile strength measurements, and n is the number of replicates (Watts and Dexter 1998). Watts and Dexter (1998) explored various methods for determining friability and recommended the coefficient of variation method as the standard for describing soil friability. The soil Fr classification used in this report is from Imhoff, Pires Da Silva, and Dexter (2002) and is presented in Table 2.

The aggregate tensile strength data were log transformed based on the residual patterns from the Proc Mixed analyses. Proc Mixed analysis of variance was done (SAS Inc., Cary, N.C.) using the splice option and the Bonferroni adjustment ($\Pr > \mathrm{F} = \alpha/2$, where 2 represents the number of treatments compared and $\alpha = 0.10$) was used to explain simple effects, significant interactions, and treatment comparisons.

Results and Discussion

Horn et al. (1995) report that when fields are irrigated, tensile strength can increase with time because of the number of wetting and drying cycles. In this study, aggregate strength was only different between bed and furrow in field 3 (Table 3). An attribute of the furrow irrigation was that furrow-irrigated fields consistently had lower tensile strength at the top of the field than at the bottom of the field (Table 4). Aggregates were 43, 35, 24, and 13%

Table 3

Analysis of variation for furrow irrigated fields (treatments represent bed or furrow, location is defined as the top or bottom of the field, and the asterisks represent $\alpha < 0.05$)

	Farm 1	Farm 3	Farm 5	Farm 7
Fixed effects	Pr > F ($\alpha = 0.05$)			
Treatment				
Aggregate strength	0.1204	0.0020**	0.7633	0.0578
Friability	0.0219**	0.3413	0.0355**	0.9369
Location				
Aggregate strength	0.0028**	0.0035**	0.0074**	0.0314**
Friability	0.2413	0.9210	0.1763	0.1256
Location × Treatment				
Aggregate strength	0.6595	0.0055**	0.1142	0.5321
Friability	0.4824	0.3833	0.0290**	0.9606

weaker at the top versus the bottom of fields 1, 5, 3, and 7, respectively. According to the analysis of variance, location in the field was significantly different for all the furrow irrigated fields (Table 3). One reason for the difference could be the lower end of furrow-irrigated field usually receives less water and dries out sooner than the upper reaches of the field. Another possible reason is that furrow irrigation erodes soil from the top end of the field and deposits soil on the bottom end (Trout 1996).

Friability in furrow-irrigated fields was in the friable range (0.20 to 0.50) for the furrow location and in the very friable range (0.50 to 0.80) for the bed samples in most fields (Table 4). Portneuf soil is usually described as very friable for the 0- to 22-cm depth. Sluka soil (field 3) is described as very friable for 0 to 10 cm and friable 10 to 28 cm. Friability is an important factor in determining soil response to tillage. By definition, a highly friable soil tends to naturally produce a suitable size aggregate distribution for crop establishment and growth with a single pass of a tillage implement. The mechanically unstable condition implies that a suitable seedbed for crops may be present without tillage and these soils should be ideal for direct drilling. A nonfriable soil suggests that there is much greater need for tillage, which increases the energy input into crop-management practices (Macks et al. 1996).

Tensile strength in most sprinkler-irrigated fields increased significantly with depth in fields 2, 4, and 6 (Tables 5 and 6). In fields 2 and 4, the tensile strength on average increased 27.5% and 59% from the 0- to 5-cm depth to the 5- to 15-cm depth, respectively. Both fields had been irrigated after harvest; however, field 2 had been disked whereas field 4 had no tillage after harvest (Table 1). In fields 8 and 9 the influence of tillage operations and irrigation were not so apparent. Field 8 used a wheel-line irrigation system and field 9 was the only field that had been planted in beans (all others had been planted with grain).

It is difficult to compare results from sprinkler- and furrow-irrigated fields in this study because each field had slightly different management practices. The range of average tensile strength was lower in the 0- to 5-cm depth in sprinkler-irrigated fields (69.6 to 208.6 kPa) when compared to the same depth in the bed and furrow locations in furrow irrigated fields (99.2 to 305.3 kPa and 116.5 to 266.0 kPa, bed and furrow, respectively). The average range of friability for the 0- to 5-cm depth was similar for both irrigation

Table 4

Mean aggregate tensile strength for soil aggregates from the furrow irrigated fields in southern Idaho (bold lettering indicates significant differences between the bed and the furrow based on the Bonferroni adjustment $\Pr > F = \alpha/2 = 0.05$)

Farm	Field location	Furrow: Top or bottom	Tensile strength (kPa)	Friability $\sigma_Y/\overline{Y} \pm \sigma_Y/(\overline{Y}\sqrt{2n})$
1	Top	Bed	116.27	0.78 ± 0.27
	Top	Furrow	144.42	0.43 ± 0.09
			Pr > F = 0.1740	**Pr > F = 0.0354**
1	Bottom	Bed	192.71	0.59 ± 0.16
	Bottom	Furrow	266.22	0.38 ± 0.07
			Pr > F = 0.0969	Pr > F = 0.1758
3	Top	Bed	99.19	0.62 ± 0.0003
	Top	Furrow	217.6	0.47 ± 0.18
			Pr > F = <0.0001	Pr > F = 0.2167
3	Bottom	Bed	185.51	0.55 ± 0.07
	Bottom	Furrow	229.15	0.53 ± 0.12
			Pr > F = 0.0360	Pr > F = 0.8438
5	Top	Bed	137.66	0.63 ± 0.02
	Top	Furrow	116.45	0.56 ±0.08
			Pr > F = 0.4428	Pr > F = 0.2156
5	Bottom	Bed	191.95	0.74 ± 0.02
	Bottom	Furrow	197.63	0.52 ± 0.09
			Pr > F = 0.2178	**Pr > F = 0.0060**
7	Top	Bed	259.3	0.70 ± 0.03
	Top	Furrow	217.1	0.70 ± 0.10
			Pr > F = 0.3020	Pr > F = 0.9555
7	Bottom	Bed	305.32	0.65 ± 0.06
	Bottom	Furrow	241.71	0.64 ± 014
			Pr > F = 0.0772	Pr > F = 0.9257

Table 5

Analysis of variation for sprinkler irrigated fields [depth (0 to 5 cm and 5 to 15 cm) is the treatment, location is defined as the top or bottom of the field, and the asterisks represent $\alpha < 0.05$]

	Farm 2	Farm 4	Farm 6	Farm 8	Farm 9
Fixed effects	Pr > F ($\alpha = 0.05$)				
Depth					
Aggregate strength	0.0168**	<0.0003**	0.0067**	0.7625	0.6590
Friability	0.3150	0.0328**	0.0259**	0.4706	0.9879
Location					
Aggregate strength	0.8408	<0.0001**	0.1900	0.4853	0.8140
Friability	0.2848	0.3518	0.2115	0.0061**	0.0119**
Location × Depth					
Aggregate strength	0.8848	0.0122**	0.1783	0.2770	0.2397
Friability	0.7085	0.1113	0.2291	0.3927	0.0902

Table 6

Mean tensile strength for soil aggregates from the sprinkler irrigated fields in southern Idaho (bold lettering indicates significant differences between depths based on the Bonferroni adjustment $\Pr > F = \alpha/2 = 0.05$)

Farm	Field location	Depth (cm)	Tensile strength (kPa)	Friability $\sigma_Y/\overline{Y} \pm \sigma_Y/(\overline{Y}\sqrt{2n})$
2	Top	0–5	176.46	0.53 ± 0.07
	Top	5–15	241.16	0.49 ± 0.02
			Pr > F = 0.0141	Pr > F = 0.3323
2	Bottom	0–5	177.03	0.49 ± 0.03
	Bottom	5–15	245.01	0.47 ± 0.06
			Pr > F = 0.0116	Pr > F = 0.6414
4	Top	0–5	172.46	0.76 ± 0.12
	Top	5–15	350.51	0.48 ± 0.05
			Pr > F = 0.0002	**Pr > F = 0.0069**
4	Bottom	0–5	69.64	0.72 ± 0.09
	Bottom	5–15	211.13	0.60 ± 0.09
			Pr > F = 0.0001	Pr > F = 0.1641
6	Top	0–5	130.93	0.78 ± 0.10
	Top	5–15	191.73	0.53 ± 0.09
			Pr > F = 0.0069	**Pr > F = 0.0215**
6	Bottom	0–5	122.48	0.62 ± 0.14
	Bottom	5–15	142.23	0.53 ± 0.08
			Pr > F = 0.1657	Pr > F = 0.3430
8	Top	0–5	151.2	0.61 ± 0.05
	Top	5–15	179.07	0.60 ± 0.08
			Pr > F = 0.3090	Pr > F = 0.9203
8	Bottom	0–5	175.65	0.44 ± 0.06
	Bottom	5–15	156.29	0.50 ± 0.05
			Pr > F = 0.5595	Pr > F = 0.2741
9	Top	0–5	208.6	0.51 ± 0.03
	Top	5–15	202.31	0.56 ± 0.10
			Pr > F = 0.5975	Pr > F = 0.2216
9	Bottom	0–5	190.25	0.45 ± 0.03
	Bottom	5–15	207.01	0.39 ± 0.02
			Pr > F = 0.2318	Pr > F = 0.1694

practices (0.44 to 0.78 for the sprinkler-irrigated fields; 0.55 to 0.78 and 0.38 to 0.70 for the bed and furrow locations of furrow-irrigated fields, respectively).

In conclusion, the data suggest that the energy from sprinkler droplets may influence the tensile strength of aggregates in the upper layer of the field but not to the detriment of the seed bed; in other words, the upper layer remained very friable as opposed to mechanically unstable or unfriable. In studies of tensile strength and friability the previous treatments of the soil are important.

The device designed to test aggregate tensile strength provided an effective, reliable, and reproducible means of collecting aggregate strength data needed to evaluate effects of agricultural management practices on soil tensile strength and friability.

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