

Tensile Strength of Air-Dry Soil Aggregates as Influenced by Short-Term Management Practices in Western Iran

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Abstract

Agricultural soil management practices including tillage, traffic and cropping systems have had a major effect on soil structure and aggregation. The objective of this study was to investigate the short-term influences of tillage and manure applications on tensile strength of air-dry aggregates of a sandy loam soil under corn crop due to different management treatments. The interactive influences of tillage (no-till, NT; chisel plow, CP; and moldboard plow, MP) and composted cattle manure applications [0, 30 and 60 Mg (dry weight) ha⁻¹] were assessed. The aggregate tensile strength (Y) was measured on the air-dry aggregates (8.0-9.4 mm) according to the indirect method. Coefficient of variation of Y values was used as an index of friability (k). Tillage and manure treatments had significant effects on the aggregate strength for the all soil layers. This implies that even for the short-term period, the soil strength was significantly affected by the management regimes. Tillage affected the aggregate strength in the order of NT>CP>MP. The high energy input in moldboard plowing might have produced micro-cracks within aggregates resulting in subsequently weaker aggregates. The low dry tensile strength under MP system implies the ease of fragmentation of the soil aggregates. Soil inversion by moldboard plow caused k to be higher in MP treatment and be in the order of MP>CP>NT among the all soil layers. The stronger aggregates in CP are probably results of less effective soil loosening by the chisel plow. The Y value of CP increased steeply in the third layer probably due to the normal and shear stresses induced by chisel plow at 15 cm depth. The manure application decreased the tensile strength of air-dried aggregate and increased k due to the crack formation in the aggregates. The overall increasing trend of soil strength with soil depth represents the non-homogeneous mixing of the manure vs. depth as well as the higher clay content of the lower layers which contribute to the soil strength. Moreover, the intensity of drying and wetting cycles during the growing season is pronounced in the upper layers. The overall relationship between Y or k and soil macro-porosity (Macro-P) among the all treatments was assessed. The Y was negatively and k was positively related to Macro-P. The close relation between Y or k and Macro-P implied the major effect of large pores on the crack propagation in the soil. The results reported here, were measured on the air-dry aggregates and from the short-term

experiment. It is also worthwhile to measure the soil mechanical characteristics over a range of water regimes, and to continue such experiments for mid- and long-term periods for the possible beneficial effects of conservational tillage systems on the soil tilth and friability.

Keywords: Moldboard plow, chisel plow, no-till, manure, aggregate tensile strength, friability, macro-porosity

Introduction

Agricultural soil management practices including tillage, traffic and cropping systems have had a major effect on soil structure and aggregation. Soil fragmentation is also a primary aim in most tillage operations in order to create a soil tilth favorable for crop establishment and growth. Management practices would influence the soil fragmentation and friability through changing the soil structure and its stabilization in different, complex and sometimes conflicting manners (Dexter, 1988; Watts et al., 1996).

Tensile strength is probably the most useful measure of strength of individual soil aggregates (Dexter and Kroesbergen, 1985). It has been used in soil friability and tillability studies (Dexter and Watts, 2000). The tensile strength of aggregates and friability are important expressions of the ease of seedbed preparation, i.e. soil workability (Dexter, 1988). A friable soil is defined as a soil where large aggregates have a low tensile strength and small aggregates a relatively large strength (Utomo and Dexter, 1981). High soil strength is necessary if soil is to retain its structure against imposed stresses. A complication with agricultural soils is that their strength must not be too great otherwise, plant roots and other organisms will not be able to penetrate through the soils (Dexter, 1988 and 1997). In general, factors those enhance clay dispersion e.g. intensive tillage have been found to result in increased tensile strength of dry aggregates and therefore reduced ease of preparing a desirable arable layer (Kay and Dexter, 1992). Evidence suggests that cementation of dispersed clay was a determining factor for the stronger increase in aggregate tensile strength with decreasing water content. Soil compaction may not only induce clay dispersion, but also increase the number of contact points between the soil elements. These factors may explain the negative effect of soil compaction on aggregate tensile strength and friability found by Chan (1989a and b), Guérif (1990) and Watts and Dexter (1998).

Conflicting results have been found regarding the influence of soil organic matter on soil fragmentation and friability. In some cases, tensile strength of dry aggregates has increased with input of organic matter or high earthworm activity. Others have found a decrease in tensile strength of dry aggregates and friability with increasing organic matter content (Watts and Dexter, 1998). The divergence in the response to organic matter content is probably related to the differentiated effect of organic matter on soil structure formation and stabilization.

The information on the effects of management systems on the tensile strength of soil aggregates is limited for most soils in Iran. Therefore, the objective of

this study was to investigate the short-term influences of tillage and manure applications on the tensile strength of dry soil aggregates in western Iran.

Materials and methods

Soil type and field experiment

The soil aggregates used in this study were obtained from a field experiment located at Agriculture Research Station in Hamadan. The climate type is semi-arid. The experiment was established in 2003 on a sandy loam soil contained 620 g kg⁻¹ of sand, 260 g kg⁻¹ of silt, and 120 g kg⁻¹ of clay with 3.4 g organic carbon kg⁻¹, 0.3 g N kg⁻¹, and pH of 8. The soil is classified as fine loamy, mixed, mesic Calcixerollic Xerochrepts according to the USDA classification. The soil has been under continuous corn production from 1993 prior to establishment of the following treatments.

Three tillage systems and three rates of manure were arranged in a split-plot design with tillage treatments as main plots and manure applications as sub-plots. Three replicates of the treatments were applied in a randomized block design. Three rates of composted cattle manure were: 0, 30 and 60 Mg (dry weight) ha⁻¹ applied manually with a very uniform distribution on the soil surface before tillage treatments' application. Chemical fertilizer was also added to the plots supplying N, P and K based on soil test recommendations. Fertilizer applications included a basal starter and side dressing rates, that were based on local recommendations. The three tillage systems consisted of: (i) No-tillage (NT) treatment, where planting was accomplished directly by hand in an undisturbed soil without any tillage operations; (ii) Chisel plow (CP) treatment involved chisel plowing to a depth of 15 cm; and (iii) Moldboard plow (MP) treatment involved complete soil inversion and crop residue to a depth of 30 cm. In addition, secondary tillage operations were applied for seedbed preparation prior to sowing in CP and MP plots. Gravimetric soil water content at 0-30 cm depth varied in the range of 16-18 % at the time of tillage operations. Corn (*Zea mays L.* cultivar 108) was planted by hand at 66000 plants ha⁻¹ in 75 cm rows. The planting date was 10 June 2003. Plots were 10 m long and 5 m wide with the long dimension up and down the 1 to 1.5 % slope. A sprinkler system was used for irrigation according to the local recommendations.

Sampling and aggregate preparation

Prior to harvesting, the soil was sampled from 0-7.5, 7.5-15 and 15-22.5 cm depths. A sampling spade was pushed gently under each soil layer to avoid deformation of aggregates during sampling. Samples were air-dried in the laboratory and stored. Aggregate samples, 6.0 to 9.4 mm across, were sieved and collected for strength measurements.

Aggregate tensile strength, soil friability and macro-porosity

The aggregate tensile strength was measured on the air-dry aggregates according to the indirect method described by Dexter and Kroesbergen (1985) and Dexter and Watts (2000). For each treatment and replication, fifteen aggregates were chosen at random. The aggregates were crushed individually between two flat parallel plates of a uni-axial test at constant strain rate of 0.83 mm min^{-1} . The compressive force was measured by a proving ring of $1000 \pm 0.4 \text{ N}$. Failure occurred when fracture was observed on the aggregate. The aggregate tensile strength (Y) was calculated from the equation:

$$Y = 0.576 \frac{F}{d_{\text{eff}}^2} \quad (1)$$

where F is the compressive force required to fracture the aggregate in tension and d_{eff} is the effective diameter of the tested aggregate which was calculated as:

$$d_{\text{eff}} = d_{\text{ave}} \left(\frac{m}{m_0} \right)^{\frac{1}{3}} \quad (2)$$

in which d_{ave} is the mean sieving diameter (i.e. $(8.0+9.4)/2 = 8.7 \text{ mm}$) equal for all of the tested aggregates. m and m_0 stand for the individual mass of the aggregate and the mean mass of the batch of fifteen aggregates, respectively. Aggregate mass was measured with $\pm 0.001 \text{ gr}$ precision. This calculation was done to adjust the aggregate diameters according to their individual diameters based on the assumption that all aggregates have equal density (Dexter and Kroesbergen, 1985; Dexter and Watts, 2000).

A simple but still useful index of friability (k) as suggested by Watts and Dexter (1998) using the standard deviation of tensile strength measurements on a single size of aggregates was calculated by:

$$k = \frac{\sigma_Y}{\bar{Y}} \quad (3)$$

where \bar{Y} and σ_Y are the mean and standard deviation of the tensile strength measurements, respectively. This can be regarded as coefficient of variation and a simple measure of soil friability where a large variation in Y for a given aggregate size may be expected to result from a more friable soil.

The effects of large soil pores on tensile strength and friability was determined by measuring the relative volume of the pores with effective diameters higher than 30 microns. These macro-porosity (Macro-P) were determined using the Young-Laplace equation of capillarity from the water retention curve data determined by sand box and pressure plate measurements (Klute, 1986) on undisturbed soil samples.

Statistical analysis

The analysis of variance of Y values was performed independently for the sampling depths subjected to the procedure of SAS (SAS Institute, 1990).

Sources of variation included tillage practices and levels of manure as well as their interactions. Significant differences were separated by Fisher protected LSD test.

Results and discussion

The analysis of variance for the aggregate tensile strength is illustrated in Table 1. The effects of tillage and manure treatments on the aggregate strength were significant for all soil layers. This implies that during the short-term, soil strength was significantly affected by the management regimes. Tensile strength was not affected by the tillage and manure interactions except for the most shallow soil surface layer.

Table 1: The *F* ratio of analysis of variance for the aggregate tensile strength among the tillage and manure treatments^a

Source of variance	df	Soil depth layers		
		0-7.5 cm	7.5-15 cm	15-22.5 cm
Tillage (T)	2	186.52**	131.81**	339.99**
Manure (M)	2	70.44**	16.50**	5.72*
T × M	4	3.30*	1.55	0.06

^a * and ** mean significant effects at 0.05 and 0.01 levels of probability, respectively.

The significant differences among tillage and manure levels on the aggregate tensile strength (*Y*) are shown in Table 2. Generally, the differences between treatments were significant. Tillage affected the aggregate strength in the order of NT>CP>MP. These data agree with aggregate stability values generated by the wet sieving method. The mean weight diameter (MWD) of the aggregates was significantly influenced by tillage methods in the same order for the all soil layers (data not shown). The low dry tensile strength under MP system implies the ease of fragmentation of the soil aggregates. The stronger aggregates in CP treatments appear to result from the less effective soil loosening by the chisel plow. Generally, tine plowing has been found to loosen the soil less effectively than moldboard plowing. The high energy input in moldboard plowing might have produced micro-cracks within aggregates resulting in subsequently weaker aggregates. These results are in agreement with the findings of Munkholm et al. (2001) on short-term effects of non-inversion tillage system. They showed that the soil under non-inversion tillage system had lower friability index and higher tensile strength of air-dry aggregates. However, Arvidsson and Feiza (1998) did not find significant differences between the tensile strength of aggregates from a silty clay soil subjected to moldboard and chisel plowing. Macks et al. (1996) even found lower tensile strength of air-dry aggregates for the reduced tilled soil than for the conventionally tilled soil.

For the third layer, *Y* values did not differ between NT and CP treatments (Table 2). The *Y* value of CP increased steeply in the third layer probably due to

the normal and shear stresses induced by chisel plow at 15 cm depth (Fig. 1-a). The high stresses on the soil beneath the chisel plow creating plow pan in the third depth which also caused the high values of bulk density and cone index. Soil inversion by moldboard plow caused the friability index to be higher in MP treatment and be in the order of MP>CP>NT among the all layers (Fig. 1-b). Munkholm et al. (2002b) also reported that compacted soil had the higher tensile strength when compared with the non-compacted soil at similar matric suctions. It should be mentioned that a well-structured soil has a low aggregate strength when dry and a high stability (low clay dispersion) when wet (Watts et al., 1996). Watts et al. (1996) reported that Y increased as the amount of dispersible clay increased. They showed that soils with a history of imposed wheeling had seedbeds made up of aggregates which were significantly stronger when dry but dispersed larger quantities of clay when shaken in water. They also reported that the friability index was higher when the soil is not compacted and/or cultivated continuously.

Table 2: The effects of tillage and manure treatments on tensile strength of soil aggregates (kPa) sample from different soil soil depths.

Tillage (T)	Rate of manure application (Mg ha ⁻¹)			\bar{X}
	0	30	60	
	0-7.5 cm soil layer			\bar{X}
No-tillage	108.3	100.8	88.5	99.2
Chisel plow	66.5	47.7	41.1	51.8
Moldboard plow	33.6	31.0	24.4	31.3
X	71.1	59.8	51.3	
LSD (0.05)	Tillage (T) 10.0	Manure (M) 3.7	T × M 6.3	
	7.5-15 cm soil layer			\bar{X}
No-tillage	115.3	105.0	101.6	107.3
Chisel plow	76.9	65.9	45.4	62.4
Moldboard plow	42.8	34.0	27.3	34.7
X	78.3	68.0	58.1	
LSD (0.05)	Tillage (T) 12.5	Manure (M) 7.7	T × M 13.3	
	15-22.5 cm soil layer			\bar{X}
No-tillage	122.0	116.4	111.4	116.6
Chisel plow	114.9	110.3	101.7	109.0
Moldboard plow	43.7	37.3	29.5	36.8
X	93.5	88.0	80.9	
LSD (0.05)	Tillage (T) 9.8	Manure (M) 8.2	T × M 14.1	

The manure application decreased the tensile strength of air-dried aggregate (Table 2 and Fig. 2-a). It means that the manure induced the crack formation and weak spots in the aggregates, as is also shown by lowering the friability index (Fig. 2-b). It is in the opposite direction of the influences on aggregate stability

since MWD increased as the manure rate increased (i.e. $60 > 30 > 0 \text{ Mg ha}^{-1}$) for the all soil depths (data not shown). Causarano (1993) also reported that large quantities of organic matter strengthened wet soil aggregates and weaken dry ones. So it seems as though the stabilizing effect of organic matter on aggregate strength is most significant in the wet range of the soil water regime. Munkholm et al. (2002a) illustrated that the aggregates of an unfertilized soil were strong when dry and weak when wet. In contrast, the long-term manured soil had strong aggregates when wet and rather weak ones when dry. They related the differences between the soils when dry to the differences in dispersible clay content, whereas the differences when wet were related to the differences in the amount of organic bindings and hydrophobicity. However, Watts et al. (1996) did not find significant effects of different application rates of farmyard manure on soil structural stability parameters e.g. aggregate tensile strength, dispersible clay and quantity of water-stable aggregates.

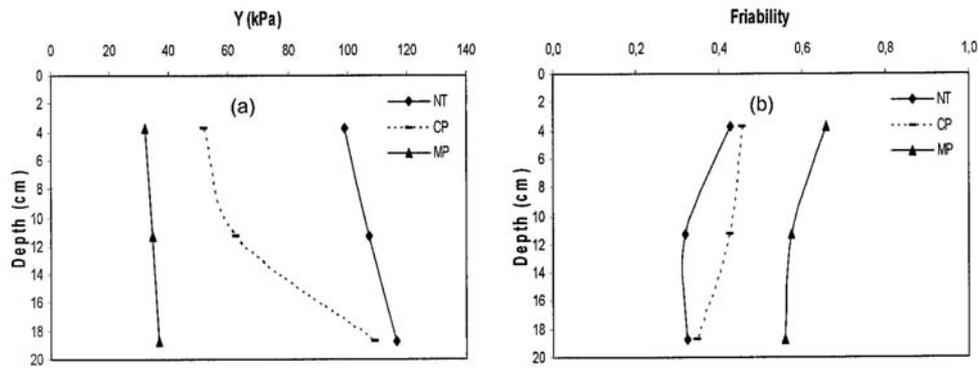


Fig. 1: Tillage systems' effects on aggregate tensile strength (a) and friability (b)

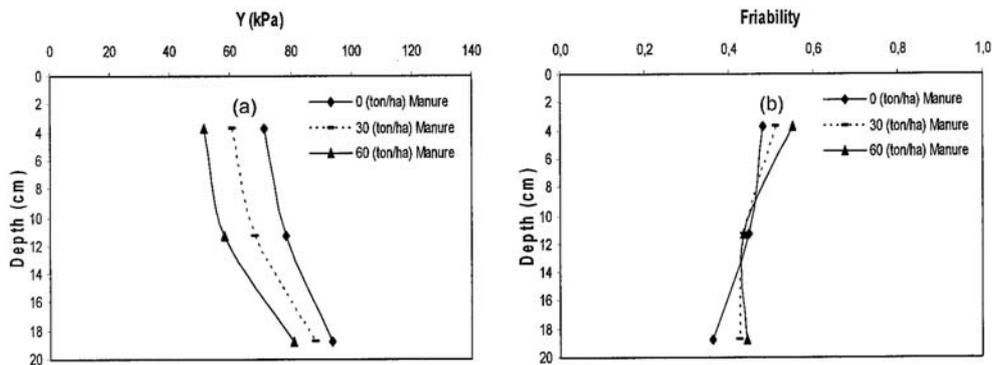


Fig. 2: Manure treatments' effects on aggregate tensile strength (a) and soil friability (b)

The overall increasing trend of manure on soil strength was soil depth, suggesting there is non-homogeneous mixing of the manure at greater depths as well as increasing clay content at greater soil depths that contributed to soil strength (Fig. 2-a). Moreover, the intensity of drying and wetting cycles during the growing season is pronounced in the upper layers. Kay et al. (1994) suggested that the tensile strength of air-dry aggregates increased with depth due to reduced severity of wetting and drying processes. Kay and Dexter (1992) explained that the wetting and drying cycles could decrease the tensile strength during the season. Decrease of strength is the cumulative effects of entrapped air and differential swelling in the soil aggregates which induce more failure zones. Noticeably, the change of tensile strength during the season may be the net result of weak spot formation and agglomeration of soil particles by cementing additional dispersible clay minerals.

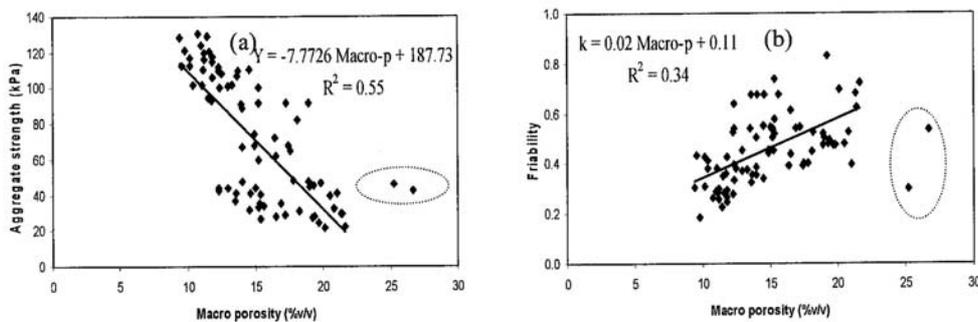


Fig. 3: Overall relationship between aggregate tensile strength and macro-porosity (a), and soil friability and macro-porosity (b). The encircled points (i.e. outliers) were not used in the regression analysis

Soil pore characteristics are expected to affect the soil mechanical behavior, especially when tensile failure occurs. Tensile failure occurs due to the propagation of cracks in the stressed samples (Hallet et al., 1995). The overall relationships between Y or k and Macro-P among the all treatments were assessed. The Y was negatively and k was positively related to Macro-P (Fig. 3). The close relation between Y or k and macro-porosity implies the major effect of large pores in the crack propagation in the soil. Guerif (1990) reported a strong negative correlation between macro-porosity and tensile strength of dry soil. Munkholm et al. (2002b) also found that tensile strength of soil cores was significantly and negatively correlated to the soil macro-porosity. The cracks and macro-pores are believed to be longer and narrower than the micro-pores. The applied tensile is concentrated more on the tip of narrower and longer pores (Snyder and Miller, 1989). Hallett et al. (1995) found that dry natural soil blocks fragmented mainly along pre-existing crack surfaces.

Conclusions

These results demonstrated the interactive effects of tillage and manure treatments on the tensile strength of air-dry aggregates and soil friability. The aggregate tensile strength and soil friability were related to the soil macroporosity implying the major effect of large pores on the crack propagation in the soil. The results reported here, were measured on the air-dry aggregates and from the short-term experiment. It might take a couple of years or more before beneficial effects of conservational tillage systems on the soil tilth and friability are observed. It is also worthwhile to measure the soil mechanical characteristics over a range of water regimes, and to continue such experiments for mid- and long-term periods. Furthermore, the results of soil fragmentation and tensile failure studies should be employed in the design of new tillage implements.

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