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# Strength and Stability of Aggregates as the Key Indicators for Evaluating Soil Physical Conditions

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Effect of long-term fertilization and manuring on strength and water stability of soil aggregates, dispersibility of clay, and their relationship with soil organic C (SOC) was evaluated on three different Indian soils. Aggregate parameters showed significant variations under the recommended and 50% higher than the recommended NPK fertilizer and fertilizer-plus-manure applications. However, tensile strength and friability of aggregates were identified as the most sensitive to either particulate organic C (POC) or total organic C (TOC) content change in the soil. Fertilizers and manure had a distinct effect on POC, a reactive form of SOC with greater response to soil management. Results suggested that monitoring the micro- or aggregate scale soil response was critical to identify the best agricultural management practice for sustaining the soil quality. Role of fertilizer alone or in combination with manure in maintaining soil physical condition through the modification of soil aggregate properties and clay dispersibility was clearly evident.

**Key words:** Clay dispersibility, long-term fertilizer experiment, soil organic C, tensile strength and friability of aggregates

Degradation of soil quality and yield-plateauing in intensive crop production systems call for understanding of the behaviour of soil at microscale under different agricultural management options. Mechanical properties of soil aggregates are fundamental for understanding the water and nutrient dynamics in soil (Peth *et al*. 2010), and are the key determinants to the limitations of soil management practices (Yang *et al*. 2013). Organic matter affects mechanical properties of aggregates, and hence fertilizer application alone or in combination with manure has differential impacts (Schjønning *et al*. 2002; Das *et al*. 2014; Chakraborty *et al*. 2014).

Mechanical properties of aggregates include tensile strength (TS), friability and water stability of aggregates. The TS is defined as the maximum force per unit area (stress) needed to cause disruption of soil aggregates. This is highly sensitive to soil structural conditions as controlled by micro-cracks or other flaws in the soil. The TS provides information of strength that needed to be overcome by the growing roots of plants (Imhoff *et al*. 2002). Friability, on the other hand, may be defined as the tendency of a soil mass to disintegrate into smaller fragments under an applied stress (Utomo and Dexter 1981), and is the most useful indicator of soil tilth (Macks *et al.* 1996).

Water stability of aggregates can be quantified by mean weight diameter (MWD) of soil aggregate sample, and is mostly used as an index of soil structural stability. Water dispersible clay (WDC) refers to the amount of clay that can be dispersed by water, and indicates soil structural stability (Igwe and Udegbunam 2008). Some portion of WDC is easily dispersed in water without any mechanical force, and is called spontaneously dispersed clay (SDC), while the amounts of clay that get dispersed by a small amount of mechanical energy are called readily dispersible clay (RDC) (Rashad *et al.* 2014). Amount of clay dispersed depends mostly on the clay content, organic matter content in soil, and also on the

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**Table 1.** Selected properties of the soils used for the study

| Property | AICRP-LTFE-Delhi | AICRP-LTFE-Ranchi | AICRP-LTFE-Pantnagar |
|---|---|---|---|
| Label | Delhi | Ranchi | Pantnagar |
| Location | IARI, New Delhi | BAU, Kanke, Ranchi, Jharkhand | GBPUA&T, Pantnagar, Uttarakhand |
| Continuing since | 1971 | 1972 | 1971 |
| Latitude | 28.63°N | 23.35°N | 29.02°N |
| Longitude | 77.16°E | 85.33°E | 79.48°E |
| US Soil Taxonomy | Typic Haplustept | Typic Haplustalf | Typic Hapludoll |
| Cropping system | Maize-Wheat | Soybean-Wheat | Rice-Wheat |
| Sand (%) | 71.7 | 66.2 | 36.2 |
| Silt (%) | 12.0 | 8.4 | 46.0 |
| Clay (%) | 16.3 | 25.4 | 17.8 |
| Texture (USDA) | Sandy loam | Sandy clay loam | Loam |
| Soil organic C (g $kg^{-1}$) | 4.4 | 4.5 | 14.8 |

exchangeable cations, particularly Fe or Al oxides which act as binding agents. Higher WDC indicates structural degradation. Dispersed clay leads to the clogging of pores and causes soil crusting, and ultimately decreases soil productivity.

Three different centres namely, Indian Agricultural Research Institute (IARI), New Delhi, Birsa Agricultural University (BAU), Ranchi and Govind Ballabh Pant University of Agriculture and Technology (GBPUA&T), Pantnagar under the All India Coordinated Research Project on Long Term Fertilizer Experiments (LTFE), were selected for the study (Table 1). All these experiments have been continuing since 1971/72 and therefore, the soils have likely attained their equilibria. Selected treatments were 100% NPK [N, P and K at 120:26:33 kg $ha^{-1}$ as urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively], 150% NPK (N, P and K at 180:39:49.5 kg $ha^{-1}$; same source as in 100% NPK), 100% NPK+FYM (100% NPK along with farmyard manure @ 15 t $ha^{-1}$ $yr^{-1}$ with an average composition of 350 g $kg^{-1}$ C, 5 g $kg^{-1}$ N, 2.5 g $kg^{-1}$ P and 15 g $kg^{-1}$ K), and the control (no fertilizer or manure application).

## Materials and Methods

Soil samples were collected from 0-15 cm layer in March-April, 2015. Samples were collected by using a trowel from three points in a plot and made into the composite sample. Samples were transferred to polythene bags, tightly secured to prevent the loss of water. Due care was taken to bring samples from Ranchi and Pantnagar to Delhi. All samples were stored in refrigerator at 4 °C till further analysis.

In the laboratory, samples were spread and large clods were gently broken into smaller fractions. Samples were then air-dried at room temperature, sieved in sizes of 5-8 and 3-5 mm. Tensile strength and friability were determined on 5-8 mm sized aggregates, while 3-5 mm size of aggregates were used for aggregate stability. All the samples were kept overnight at 40 °C to achieve similar soil water in the aggregates prior to analysis.

*(a) Tensile strength and friability of aggergates*

A total of 20 numbers of aggregates (5-8 mm) were selected for each plot. Weight, length, breadth and height of each aggregate from a lot were recorded. Each aggregate was then placed between two round plates of an apparatus which was made by following the principles of modulus of rupture, and the force ($P$) needed to crush the aggregate was recorded (Das *et al.* 2014). The strength of an aggregate (TS) was computed using the following equation:

$$TS = 0.576\left(\frac{P}{D^2}\right) \qquad \text{…(i)}$$

where, $P$ is the applied force at which the aggregate breaks (Newton) and $D$ is the effective diameter (cm) of each aggregate; 0.576 is the proportionality constant. The effective diameter, $D$ of each aggregate was computed as:

$$D = D_m\left(\frac{M}{M_m}\right)^{1/3} \qquad \text{…(ii)}$$

where, $D_m$ is the mean diameter (cm), which is the average of length, breadth and height of the aggregate sample, $M$ is the dry mass of the aggregate (g), and $M_m$ is the mean of mass of 20 aggregates as representative of a treatment (g).

The friability of the aggregates was the ratio of standard deviation ($\sigma_Y$) to the mean ($\bar{Y}$) of the measured values of TS of 20 aggregates (representing a treatment) as:

$$F = \frac{\sigma_Y}{\overline{Y}} \qquad \text{…(iii)}$$

*(b) Aggregate stability*

Aggregate stability was determined following two pre-treatments, fast and slow wetting of the aggregates, as proposed by Le Bissonois (1996). In fast wetting, oven-dried (40 °C) soil aggregate samples (3-5 mm) were weighed close to 5 g and were slowly taken to a 250 mL beaker containing 50 mL distilled water. The water was carefully siphoned off after 10 min, without disturbing the aggregates. The aggregates were then transferred to a sieve of 0.053 mm, which was already immersed in methanol in a plastic container. All the aggregates from the beaker were transferred by slowly rinsing with distilled water (due care was taken again not to disturb the wet aggregates). The sieve was gently moved up and down (5 cm) for 3 min. These particles, retained over >0.053 mm sieve, were then transferred to a paper and oven-dried at 105 $^0$C. After that oven-dried samples were gently sieved manually through a set of sieves (2.0, 1.0, 0.5, 0.25, 0.1 and 0.053 mm) for 1 min, and weight of aggregate samples retained over each sieve was determined. The MWD of aggregates was calculated as an index of aggregation by using the following using:

$$MWD = \Sigma XiWi \qquad \text{…(iv)}$$

where, $X_i$ is the mean diameter of the class (mm) and $W_i$ is the weight of aggregates retained over sieve of $X_i$ diameter.

In slow wetting pre-treatment method, ~5 g soil samples were taken and kept at 1 kPa matric potential in a hanging water column for gradual wetting of aggregates. After 30 min, wet aggregates were transferred to a 0.053 mm sieve previously immersed in methanol for the measurement of aggregate size distribution as described in the fast wetting procedure.

*(c) Mechanically dispersible clay content*

Measurement of mechanically dispersible clay was made following Czyz and Dexter (2015). Soil sample of ~5 g (oven-dried at 40 °C) was placed in a 150 mL glass bottle to which 125 mL distilled water was added. The bottle was manually shaken end-to-end for 4, 8, 16 and 32 times (number of inversions, N), and allowed to settle for 16 h. After 16 h, 25 mL of soil-water suspension was pipetted out from the centre of the bottle to a turbidity meter cell. The turbidity of the suspension was recorded with a Hach 2100AN turbidimeter and expressed in NTU (Nephelometric Turbidity Units). The NTU values so obtained were converted into NTU in g of soil $L^{-1}$ of water.

The energy equivalent to the number of inversions was computed by using the formula as:

$$E_N = NWgh_a \qquad \text{…(v)}$$

where, N = number of inversions; W = mass of water, kg; g = acceleration due to gravity, 9.8 m $s^{-2}$; and $h_a$ = height of the air bubble, which was the distance between the solution surface and the top of glass bottle (measured as 0.068 m). The specific energy, $SE_N$ would be:

$$SE_N = E_N / m_d \qquad \text{…(vi)}$$

where, $m_d$ is the mass of the dry soil. Values of specific energy for N = 4, 8, 16 and 32 were estimated to be 67, 133, 267 and 533 J $kg^{-1}$, respectively. This value of specific energies lies in the same range as that of obtained in the case of primary tillage in the field. Specific energy values for the latter were found to be 50, 100 and 300 J $kg^{-1}$ with tynes, mouldboard plough and rotary tiller, respectively. The NTU value corresponding to N=4 was taken as readily dispersible clay (RDC), which is corresponding to the minimum mechanical energy inputs to the soil.

*(d) Particulate organic carbon*

The particulate organic C (POC) was isolated as per the procedure described by Cambardella and Elliott (1992). A 10 g of soil sample (<2 mm) was dispersed with 30 mL of sodium hexametaphosphate (5 g $L^{-1}$) solution and placed in a mechanical shaker for 15 h with a speed of 90 rpm. The dispersed soil samples were then passed through a 0.053 mm sieve. The fraction retained on the sieve was collected and dried at 50 ºC, and used for POC analysis. The TOC data of selected treatments was collected from AICRP-LTFE report (2012-13) of Ranchi and Pantnagar for the respective soil, and from Chakraborty *et al*. (2010) for the Delhi soil.

*Statistical analysis*

The preliminary interpretation of data was performed by using MS Excel. The NARS SAS portal was used for testing the significance at $p=0.05$ among the treatments in a location following randomised block design. The slope of the regression between the aggregate parameters and soil C was determined by using R statistical programme (2013).

## Results and Discussion

*Aggregate strength and friability*

Tensile strength of aggregates decreased with addition of fertilizer alone or in combination with

**Table 2.** Tensile strength (TS, kPa) and friability (F) of air-dry soil aggregates under the selected treatments of LTFEs

| Treatments | Delhi | | Ranchi | | Pantnagar | |
|---|---|---|---|---|---|---|
| | TS | F | TS | F | TS | F |
| 100% NPK | 168.8[a] | 0.48a | 199.3b | 0.24a | 148.6a | 0.51a |
| 150% NPK | 186.0[a] | 0.48a | 199.4b | 0.27a | 145.5a | 0.49a |
| 100% NPK+FYM | 136.2[a] | 0.47a | 179.7b | 0.32a | 134.8a | 0.54a |
| Control | 191.5[a] | 0.36b | 255.7a | 0.26a | 139.7a | 0.47a |
| P value | 0.73 | 0.04 | 0.04 | 0.29 | 0.90 | 0.52 |

Values in a column followed by same letter are not different at $p < 0.05$

FYM (Table 2). Lower TS with better agricultural management could be attributed to higher organic C content, instigating less cohesion between soil particles during drying. Similar results were published by Munkholm *et al.* (2002), Arthur *et al.* (2012) and Schjønning *et al.* (2007). Irrespective of treatments, lowest average TS was recorded at Pantnagar site (142 kPa) followed by Delhi (171 kPa) and highest TS was recorded at Ranchi site (209 kPa). However, the effect was significant only for Ranchi soil, where TS of aggregates was lower with fertilizer and organic inputs (30% lower in 100% NPK+FYM) and with fertilizer only (22% lower in 100% NPK and 150% NPK) and, compared to control. Abid and Lal (2009) and Zhang (1994) also mentioned lesser TS in soils having lower TOC content. In contrary, some authors reported greater TS associated with crop residue addition (Blanco-Canqui and Lal 2007; Carrizo *et al.* 2018). The friability of aggregates in 100% NPK, 150% NPK or 100% NPK+FYM was 30-33% higher in Delhi soils. Neither the TS nor the friability showed significant variations among treatments in Pantnagar soils, possibly due to higher native SOC content (14.8 g $kg^{-1}$) in this soil. This soil also had the lower TS and higher friability values, compared to the soils in other locations. Among all the locations, 100% NPK+FYM recorded the lowest TS (135-180 kPa), while control exhibited the greatest TS (140-256 kPa). The friability, on the other hand, recorded marginally higher values in 100% NPK+FYM treatment (0.32, 0.47 and 0.54 for Ranchi, Delhi and Pantnagar soils, respectively) compared to other nutrient management options. Organic matter makes the soil friable thereby increasing the easiness to work on (Munkholm *et al.* 2002; Schjønning *et al.* 2009). Lower TS and higher friability signifies a better soil tilth condition, which is tillage-friendly and conducive for root development. Clay content also played a dominant role in soil friability. Higher clay content in Ranchi soils (25%) resulted lower friability (39-46%) than the other two soils which have lower clay content (16-18%). Munkholm (2011) also explained lower friability associated with higher clay content due to its effect on soil strength and pore characteristics.

The MWD of aggregates in fast wetting treatment had, in general, lower values than those in the slow wetting (Table 3). Results indicated that fast wetting treatment which imitates the natural events more closely (like rainfall and irrigation), was better in defining the treatment-difference than the slow wetting of aggregates. However, treatment effect was only significant in Delhi and Ranchi soil in fast wetting whereas treatment effect was non-significant in Pantnagar soil. 100% NPK+FYM and control resulted significantly higher (30-45%, $p<0.05$) and lower (3-10%, $p<0.05$) MWD of aggregates compared to other treatments in Delhi and Ranchi soils, respectively. Better aggregate stability in 100% NPK + FYM in Delhi was due to organic inputs (Bandyopadhyay *et al.* 2010; Karami *et al.* 2012). Fast wetting treatment is more effective in soils containing high organic C, while slow wetting, which involves lower energy, responds more in loosely aggregated soils (Le Bissonnais 1996). Although soils

**Table 3.** Mean weight diameter (mm) of aggregates after fast and slow wetting treatments

| Treatments | Fast wetting | | | Slow wetting | | |
|---|---|---|---|---|---|---|
| | Delhi | Ranchi | Pantnagar | Delhi | Ranchi | Pantnagar |
| 100% NPK | 0.17b | 0.20a | 0.18a | 0.32a | 0.32a | 0.31a |
| 150% NPK | 0.18b | 0.21a | 0.17a | 0.30a | 0.34a | 0.33a |
| 100% NPK+FYM | 0.24a | 0.20a | 0.18a | 0.32a | 0.34a | 0.33a |
| Control | 0.16b | 0.19b | 0.18a | 0.31a | 0.32a | 0.36a |
| P value | 0.02 | 0.04 | 0.49 | 0.93 | 0.38 | 0.12 |

*Values in a column followed by same letter are not different at $p < 0.05$*

**Table 4.** Mechanically dispersible clay (NTU $g^{-1}$ $L^{-1}$) in soils of selected treatments from the LTFE at Delhi, Ranchi and Pantnagar under different energy inputs

| Treatments | Delhi | | | | Ranchi | | | | Pantnagar | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4# | 8 | 16 | 32 | 4 | 8 | 16 | 32 | 4 | 8 | 16 | 32 |
| 100% NPK | 0.65ab | 0.85a | 1.23b | 1.41b | 0.39ab | 0.47a | 0.65a | 1.08a | 0.48a | 0.62a | 0.85a | 1.36a |
| 150% NPK | 0.64ab | 0.89a | 1.39ab | 1.58b | 0.34b | 0.46a | 0.65a | 1.52a | 0.50a | 0.69a | 0.84a | 1.05a |
| 100% NPK+FYM | 0.51b | 0.86a | 1.29b | 1.69b | 0.35ab | 0.49a | 1.28a | 0.96a | 0.50a | 0.74a | 0.90a | 1.87a |
| Control | 0.73a | 1.07a | 1.83a | 2.14a | 0.55a | 0.74a | 0.96a | 1.60a | 0.67a | 0.79a | 1.01a | 1.86a |
| P value | 0.04 | 0.04 | 0.02 | 0.15 | 0.02 | 0.34 | 0.61 | 0.58 | 0.81 | 0.89 | 0.77 | 0.49 |

*#Number of inversions, N (equivalent to energy input levels); Values in a column followed by same letter are not significantly different at $p<0.05$*

of both Delhi and Ranchi had low organic C, but slow wetting could not able to differentiate the treatment effects.

*Clay dispersibilty*

Mechanically dispersible clay (MDC) content in soils increased with the number of inversions (Table 4). The MDC values were significantly different among treatments for soils of Delhi and Ranchi with 4 number of inversions, equivalent to 67 J $kg^{-1}$ energy draft. This is defined as readily dispersible clay (RDC). The 100% NPK+FYM resulted in significantly lower RDC (81%, $p<0.05$) in Delhi soils, while in Ranchi soil, 150% NPK resulted in lower RDC (38%, $p<0.05$) compared to control. In Pantnagar, treatment difference was not found in none of the inversions, presumably due to high native SOC. With higher energy inputs, 100% NPK+FYM treatment reduced the RDC compared to other treatments in Delhi soils, but was not effective in other locations. Lower MDC or RDC indicates a better soil structure providing resistance to dispersion, erosion or crusting.

Application of nutrients alone or in combination with FYM decreased the clay dispersibility and consequently increased the aggregate stability, irrespective of site. Balanced nutrition favours better crop growth and soil gets more plant biomass (root biomass) which in turn increases the organic carbon status. A number of authors mentioned the beneficial role of organic carbon in reducing the dispersible clay content (Rhoton 2000; Shaw *et al.* 2002). Decease in aggregate stability led to increased clay dispersibility, which was evident in Delhi soils where 100% NPK+FYM showed higher stability of aggregates ensuing lower dispersible clay. As the mechanical energy increased, the amount of clay dispersed increased too. Addition of organic matter increased the aggregate stability thereby decreasing the amount of clay dispersed (Dexter and Czyz 2000). Better friability and stability of aggregates might be due to organic matter addition in the form of FYM, although soil texture plays a pivotal role. More clay content does not necessarily increase the MDC. In Ranchi soils, addition of FYM resulted in lower MDC (or RDC) compared to the same treatment in Delhi soil. Both the soils had similar organic C content, but Ranchi soil had higher clay content (25.4%) than Delhi soil (16.3%).

*Particulate organic carbon*

The POC ranged between 0.05-0.19% for Delhi soils, 0.04-0.06% for Ranchi soils and 0.14-0.23% for Pantnagar soils (Fig. 1). In all the locations, fertilizer and organic manure significantly increased the POC. Except for the Ranchi soils, treatment 100% NPK+FYM recorded the highest POC content; in soils of Ranchi, all the fertilizer-manure treatments had similar POC content. The POC:TOC ratio had ranges between 0.11 and 0.28, but no trend was apparent.

*Relation between soil aggregate properties and carbon content*

Linear regressions between aggregate parameters and SOC for individual locations did not show any significant relation, except for RDC and POC (and POC/TOC ratio) in Delhi soils and for friability with

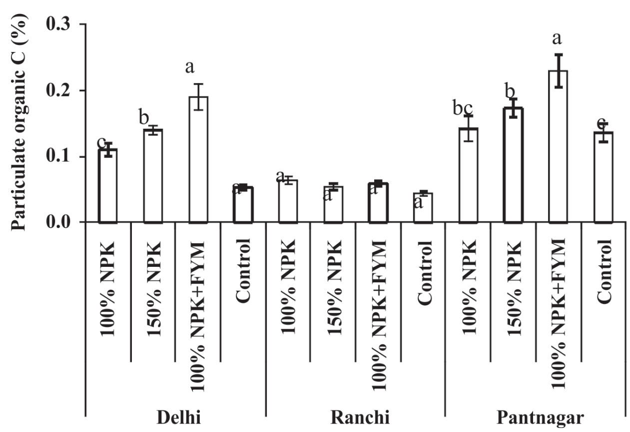


**Fig. 1.** Particulate organic C under different treatments as affected by long-term fertilizer and manure applications in three locations (vertical bars represent ±SE of mean)

**Table 5.** Slope of linear regression between soil aggregate parameters and soil organic C across treatments and locations (N=12), and TOC and POC ratio

| Aggregate parameters* | POC | TOC | TOC/POC |
|---|---|---|---|
| MWD-FW | -0.015(0.892)# | -0.015(0.449) | 0.001(0.455) |
| MWD-SW | -0.003(0.97) | 0.0001(0.994) | 0.00005(0.957) |
| TS | 476. 8(0.001) | 72.9(0.017) | -3.7(0.063) |
| F | 1.55(0.0002) | 0.24(0.007) | 0.01(0.058) |
| RDC | 0.288(0.665) | -0.018(0.881) | 0.008(0.289) |

*MWD: mean weight diameter of aggregates; FW: fast wetting; SW: slow wetting; TS: tensile strength; F: friability; RDC: readily dispersible clay; POC: particulate organic C and TOC: total organic C;
# slope of regression followed by *p*-values in parentheses

POC/TOC ratio in Pantnagar soils, possibly due to few number of data points. Our data are, therefore, inconclusive in identifying the best treatment across the three locations. Linear regression with pooled data (across locations and treatment), however, shows significant decrease in TS, and increase in friability of aggregates with bulk soil POC or TOC content. Other soil aggregate attributes did not show significant relationships with either POC or TOC, or ratio of POC and TOC. The POC has been regarded as the most responsive form of soil C to soil management practices. Therefore, the sensitivity of strength and friability of aggregates to change in POC in soil may be considered as the most critical response of soil to fertilizer and manure inputs. Although the role of FYM was evident, recommended fertilizer application could be equally effective on providing better aggregate strength and stability, and minimize dispersibility of clay.

The present study concludes that the tensile strength and friability are the best indicators to changes in soil physical environment at the micro-scale. These parameters have close relation with bulk soil C or the particulate organic C. An improvement in soil carbon signifies a better soil quality, where the aggregate tensile strength tends to decrease or the friability tends to increase. Therefore, soil aggregates strength may be included in the framework of soil health monitoring across agroecologies and management practices.

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