Bulgarian Journal of Agricultural Science, 22 (No 4) 2016, 655–664
Agricultural Academy

SOIL FRAGMENTATION PRODUCED BY SOIL CUTTING AS INFLUENCED BY VARIOUS MOISTURE CONTENTS NEAR THE SOIL'S STICKY LIMIT

A. TAGAR[1,2], J. CHANGYING[1*], D. QISHUO[1], J. ADAMOWSKI[3] and J. MALARD[3]
[1] *Nanjing Agricultural University, College of Engineering, Nanjing 210031, P. R. China*
[2] *Sindh Agriculture University, Faculty of Agricultural Engineering, Tandojam, 70060 -Pakistan*
[3] *McGill University, Department of Bioresource Engineering, Quebec, Canada, H9X3V9*

Abstract

TAGAR, A., J. CHANGYING, D. QISHUO, J. ADAMOWSKI and J. MALARD, 2016. Soil fragmentation produced by soil cutting as influenced by various moisture contents near the soil's sticky limit. *Bulg. J. Agric. Sci.*, 22: 655–664

Soil fragmentation is greatly influenced by the moisture status. The optimum moisture content W_{opt} for a seedbed may be defined as the moisture content at which tillage produces more than 50% of medium size aggregates (0.5–8 mm). The objective of this study was to investigate soil fragmentation produced by soil cutting at five moisture contents (110%, 100%, 90%, 80% and 70% of moisture content at the sticky limit of the soil, W_{SL}) to assess soil fragmentation and optimum moisture content for seedbed in dry land and paddy soils. The highest fractal dimensions were found at 70% W_{SL}, whilst lowest fractal dimensions were found at 110% W_{SL} in both dry land and paddy soils. Similarly, in both soils, the highest specific surface area was observed at 70% W_{SL}, whilst the lowest was found at 110% W_{SL}. The optimum moisture content for seedbed was observed at 80% W_{SL} for dry land soil and 90% W_{SL} for paddy soil.

Key words: seedbed; soil moisture content, sticky limit of soil

Introduction

The soil fragmentation is greatly influenced by the moisture status (Mosaddeghi et al., 2009). Indeed, Watts and Dexter (1998) concluded that soil friability is strongly affected by soil moisture content.

According to Rounsevell (1993) field operations should not be carried out when soil moisture contents are close to or exceed the lower plastic limit. Under such conditions, soil particles are surrounded by a film of water, and the soil undergoes plastic deformation (Keller and Dexter, 2012). The sticky limit is the gravimetric moisture content above which soil adheres or sticks to a steel spatula (Lal and Shukla, 2004). Baver et al. (1972) suggested that the knowledge of the sticky limit is important in deciding when to plough a plot of land.

Soil fragmentation results in the combined presence of clods, crumbles and peds and is characterized by their size, shape and surface roughness. The size is commonly used in relation to agronomic and environmental processes (Díaz-Zorita et al., 2002), which either directly or indirectly affects crop establishment and the development of root systems through restrictions to aeration and moisture content within the soil (Atkinson, 2008).

During the past few decades, many studies have been conducted to investigate aggregate size distribution for achieving better crop emergence and root development. For

---

Corresponding author: chyji@yahoo.com

example, a better seed-soil contact can be obtained if seeds and soil aggregates are of similar size (Brown et al., 1996), the finer the aggregate size the better the emergence of crop (Brown et al., 1996; Dürr and Aubertot, 2000; Guérif et al., 2001; Håkansson et al., 2002), the distribution of soil aggregate size less than 4 mm (Håkansson and Polgàr, 1984; Nasr and Selles, 1995), at least 50% aggregates <5 mm (Håkansson et al., 2002), and 1–5 mm size aggregates with at least 15% < 250 µm (Russell, 1973). According to Braunack and Dexter (1989) the optimal seedbed is produced by 0.5–8 mm aggregates. A very large fraction of small aggregates (<0.5–1 mm) is not desirable, because of increased risk of wind and water erosion, while a very large fraction of aggregates larger than 8 mm is not desirable, because of a reduction in the soil/root contact area and a higher impedance to root penetration (Munkholm, 2002).

The definition of optimum moisture content for a seedbed, W_{opt}, defined as the moisture content at which tillage produces the largest number of small aggregates and smallest number of large aggregates (Dexter and Bird, 2001) does not fit in the above conditions. Therefore, following Braunack and Dexter (1989), the optimum moisture content W_{opt} for seedbed may be defined as the moisture content at which tillage produces more than 50% of medium size aggregates (0.5–8 mm) and the least proportion of small (< 0.5 mm) as well as large (> 8 mm) aggregates.

Many studies have reported that W_{opt} is slightly below the lower plastic (or lower Atterberg) limit, PL (e.g. Ojeniyi and Dexter, 1979; Utomo and Dexter, 1981; Watts and Dexter, 1998; Mueller et al., 2003; Barzegar et al., 2004), corresponds to the moisture content at the inflection point, θ_{INFL}, on the soil water release curve (Dexter and Bird, 2001; Keller et al., 2007), is equal to 70% of the gravimetric moisture content at −5 kPa (Mueller et al., 2003), or corresponds to the moisture content at maximum proctor density (Wagner et al., 1992). Some authors have developed equations for the prediction of the optimum moisture content for seedbed (Muller et al., 2011). To our knowledge, soil fragmentation produced near the soil's sticky limit has not been studied particularly with respect to the optimum moisture content for a seedbed. Therefore, this study was designed to investigate: (i) the soil fragmentation produced by soil cutting at various moisture contents near the sticky limit of soil and (ii) the optimum moisture content for seedbed following Braunack and Dexter (1989).

Materials and Methods

The following experiments were carried out in an indoor soil bin test rig developed at the Department of Agricultural Mechanization, College of Engineering, Nanjing Agricultural University (NJAU), China.

Soil

The soils used in this experiment were dry land soil and paddy soil (yellow-brown soils in Chinese Soil Taxonomy and Halpudalf in US classification). The paddy soil was used for a rice-wheat rotation on the university's Jiangpu Experimental Farm, while the farm's dry land soil was used to cultivate vegetables such as potatoes (*Solanum tuberosum* L.), tomatoes (*Solanum lycopersicum* L.), eggplants (*Solanum melongena* L.) and chilies (*Capsicum* sp.).

Soil texture class was found quantexture using the Hydrometer Method (Bouyoucos, 1927). The sticky limit of soil was measured as the gravimetric moisture content at which soil fails to stick or adhere to a stainless steel spatula when the spatula blade was drawn across the face of the moist unkneaded mass of soil, exerting a firm pressure against the soil (Baruah and Barthakur, 1997). The lower plastic limit was determined as the gravimetric moisture content at which a soil just begins to crumble when it is rolled into a thread of 3 mm diameter to determine the liquid limit, a 30° cone bearing a total weight of about 80 g, was mounted on a shaft and allowed to rest on a cup (100 ml) full of soil for 5 seconds. The soil moisture content corresponding to a penetration of 20 mm on the linear relationship between soil moisture content (*x*-axis) and penetration (*y*-axis) was considered to be the cone penetrometer liquid limit (Campbell, 2001). Organic carbon content was found using the Walkley and Black (1934) method. Shear strength parameters such as cohesion and internal friction angle were measured using a direct shear box apparatus (Fredlund and Vanapalli, 2002), whilst cone index was directly measured with a digital soil compaction meter (TJSD-750, Zhejiang Top Instrument Co., Ltd, China). These properties are shown in Table 1.

Soil preparation

The soil was air dried for two to three weeks, then ground, and passed through a 4 mm sieve. Composite soil samples were taken from the sieved soil to determine the soil's existing moisture content, and then on the basis of existing moisture content a calculated amount of water was added to the soil using the following relation:

$$V_a = V_{req} - V_{ex} = (SMC_{req} \times WS) - (SMC_{ex} \times WS), \quad (1)$$

where V_{req} is the volume of water which needs to be added to the soil in order to achieve the desired soil moisture content (ml),

Table 1
Soil properties used in the experiment

Soil	Sand (%)	Silt (%)	Clay (%)	Textural Class	Sticky limit (g kg^{-1})	P Plastic limit (g kg^{-1})	Liquid limit (g kg^{-1})	Cohesion (kPa)	Internal friction angle (°)	Cone index (kPa)	Organic Carbon (g kg^{-1})
Dry land soil	67	5	28	Sandy clay loam	15.0	22	32	11.76	26	106	8.4
Paddy soil	50	26	24	Sandy clay loam	17.7	32	45	9.8	29	109	9.6

V_{ex} is the existing water present initially in the dry sieved soil (ml),
SMC_{req} is the required moisture content (g kg^{-1}),
SMC_{ex} is the moisture content of the dry sieved soil (g kg^{-1}),
WS is the weight of soil (g).

Water was added as a fine spray so as to attain the desired moisture content at 110%, 100%, 90%, 80% and 70% of sticky limit of soil. Soil was then well mixed in order to obtain a homogenous soil specimen, covered with a polyethylene sheet to prevent evaporation, and left for 24 hours to equilibrate to uniform moisture content. The soil was transferred to a metal-framed mold (300 mm x 100 mm x 100 mm), the mold was shifted to the hydraulic press and then it was compacted using the hydraulic jack as shown in Figure 1. To measure dry bulk density of soil molds, undisturbed soil cores (50 mm diameter, 50 mm height) were sampled at three different locations of each mold. These samples were then weighed, oven dried, reweighed and the average dry bulk density at which the molds were prepared was calculated using the gravimetric method (Blake and Hartge, 1986). The gravimetric moisture contents corresponding to 110%, 100%, 90%, 80% and 70% of the moisture content at the sticky limit, W_{SL}, and dry bulk density of dry land soil and paddy soil are shown in Table 2.

Soil cutting test rig

A safe and easy to operate test rig was developed for this study. Its main features included a soil bin, tool bearing, cutting tool, and hydraulic system. The rectangular steel tubings (90 mm × 40 mm × 5 mm), were cut into two sizes (i.e., 8 × 1000 mm and 16 × 600 mm), and were joined with bolts to construct a 2000 mm long and 600 mm wide test rig (Figure 2). Two railings were provided on the test rig; a soil bin (500 mm long × 300 mm wide) with two supports (90 mm ×40 mm × 50 mm) on the right side and one at the front that was mounted on the railings, fixed through steel screws. The height of the supports was kept minimal to avoid boundary

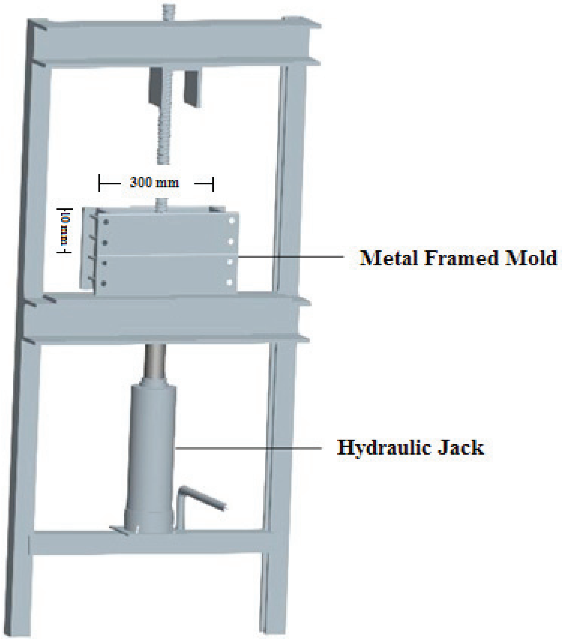

Fig. 1 Hydraulic press

Table 2
The dry bulk density at various moisture contents near the sticky limit of dry land and paddy soils

Type of soil	% Moisture content	Moisture content (%)	Dry bulk density (g cm^3)
Dry land soil	110	16.5	1.27
	100	15.0	1.22
	90	13.5	1.29
	80	12.0	1.32
	70	10.5	1.35
Paddy soil	110	19.47	1.24
	100	17.7	1.25
	90	15.93	1.29
	80	14.16	1.31
	70	12.39	1.36

friction issues. Two steel sheets (200 mm × 150 mm × 10 mm) were fixed in the test rig at a distance of 100 mm on the left and right side of the soil bin, and the tool bearing was attached. Holes (15 mm diameter) were drilled into steel sheets at different angles so that rake angles could be adjusted according to the conditions tested (e.g., Nalavade et al., 2010; Aluko and Seig, 2000; Rajaram and Erbach, 1998). The soil molds were then transferred to the soil bin. In order to move the soil bin to perform cutting operations, the soil bin was connected through a hydraulic cylinder to a hydraulic system powered by an electric motor (2.2 kW). A two way solenoid valve was provided to move the soil bin (i) to perform cutting operations and (ii) to take it back to its original position.

Soil cutting test procedure

The soil cutting test was performed at five moisture contents corresponding to 110%, 100%, 90%, 80% and 70% of the moisture content at the sticky limit of soil. A flat triangular shaped tool (150 mm long, 120 mm wide and 4 mm thick) was used at a constant speed of 10 mm s^{-1}, 15° rake angle and 30 mm depth in the experiment as shown in Figure 3.

Mass fractal dimension (Dm)

In order to calculate the mass fractal dimension at moisture contents of 110%, 100%, 90%, 80% and 70% of sticky limit of soil, three replications of total aggregates produced by cutting about 7.72 liters of dry land soil and 5.71 liters of paddy soil for each replication were collected and shifted to aluminum boxes. The aluminum boxes were left to air drying at room temperature for 15 days. The air-dried soil samples were passed through a nest of sieves with the apertures of 64–32; 32–16; 16–8; 8–4; 4–2; 2– 1; 1-0.5; 0.5–0.25 and <0.25 mm respectively. The mass of soil retained within each size class was collected and weighed. The following relation was used to calculate mass fractal dimensions:

$$Dm = 3 - \frac{\log \dfrac{M_{(r<R_i)}}{M_{tot}}}{\log\left(\dfrac{R_i}{R_{max}}\right)} , \tag{2}$$

where D_m is the mass-fractal dimension;

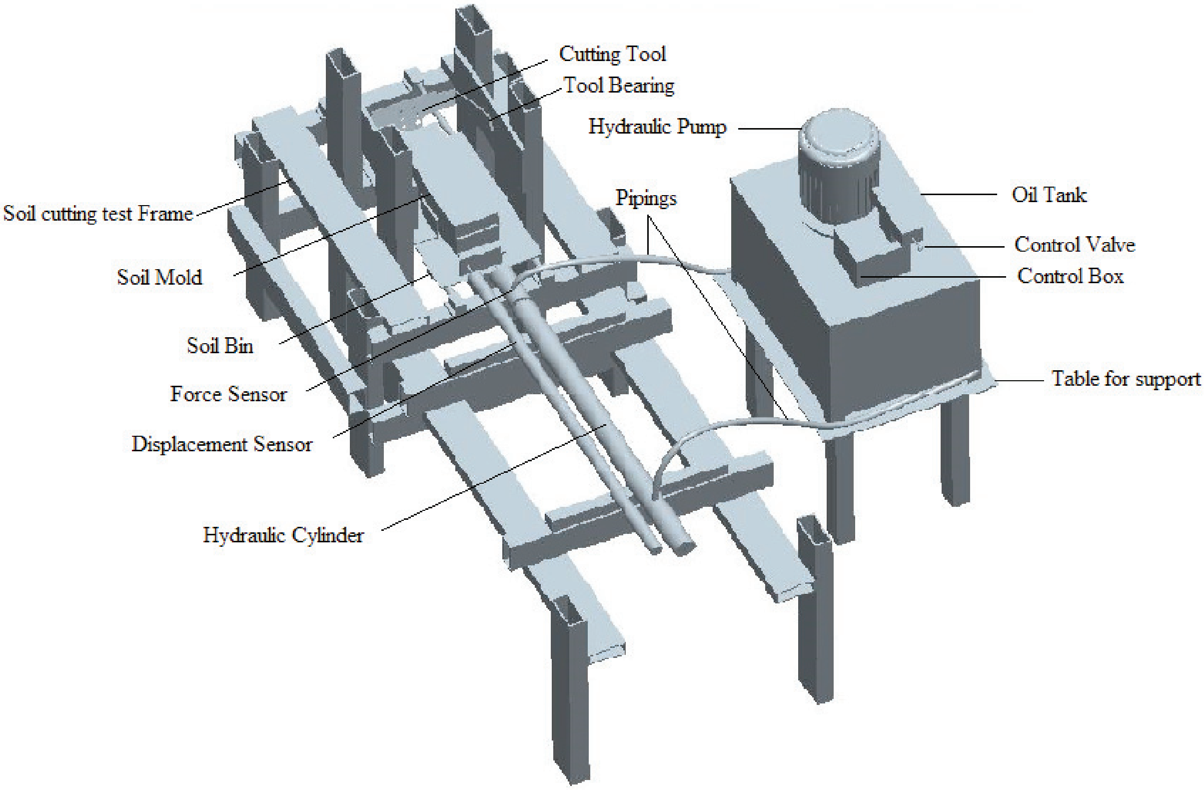

Fig. 2 Soil cutting test rig used in the experiments

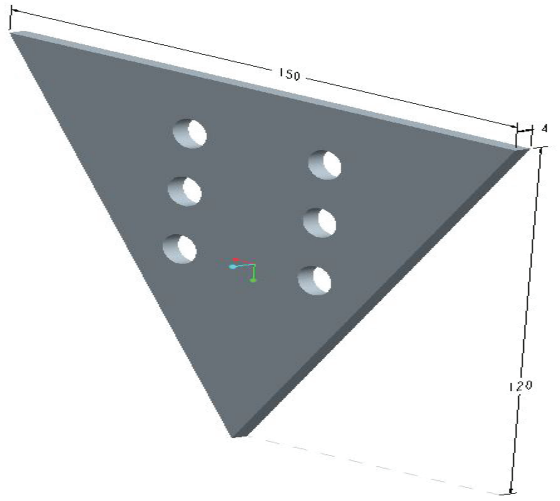

Fig. 3 Cutting tool used in the experiment

$M_{(r<R_i)}$ is the cumulative mass of aggregates of size r less than R_i;

M_{tot} is the total mass

R_{max} is the mean diameter of the largest aggregate.

The specific surface area per volume of soil ($A_{specific}$) was calculated as (Hadas and Wolf, 1983):

$$A_{specific} = A\frac{\rho}{W} = (\sum A_i)\frac{\rho}{W} = (\sum \frac{6W_i}{\rho(\phi_i \cdot \phi_{i+1})^{0.5}})\frac{\rho}{W} \quad (3)$$

where A is the total surface area produced (m^2),

A_i is the area of each aggregate size fraction (m^2),

W is the total mass of the sieved soil (kg),

W_i is the weight of fraction i (kg),

ρ is the dry bulk density (10^3 kg m^{-3}),

ϕ_i and ϕ_{i+1} are, respectively, the lower and upper limit of aggregate diameter for each size fraction (m)

Optimum moisture content

Following the definition of Braunack and Dexter (1989) for optimum moisture content for seedbeds, the nine sieve size ranges were divided into three main size ranges: 8–64 mm as large aggregates or clods, 0.5–8 mm as medium or desirable aggregates and < 0.5 mm as small aggregates. The optimum moisture content for seedbed was considered as the moisture content at which tillage produces more than 50% of medium size aggregates (0.5–8 mm) and the least proportion of small (< 0.5 mm) as well as large (> 8 mm) aggregates.

Statistical Analysis

Analysis of variance (ANOVA) was performed to evaluate the significance of moisture content at 110%, 100%, 90%, 80% and 70% of sticky limit of dry land and paddy soils on aggregate size distribution and specific surface area in a factorial design with three replications using SPSS-16.0 (SPSS, 2007). The means were compared via the least significant difference method (LSD) at $P = 0.05$.

Results

Statistical analysis of the results revealed that soil moisture contents near the sticky limit significantly ($P < 0.05$) affected aggregate size distribution of both dry land and paddy soils when all aggregate size ranges were taken in to account (Table 3).

Table 3

Aggregate size distributions at various moisture contents near the sticky limit of dry land and paddy soils

Type of soil	(%) Moisture content	< 0.25	0.25–0.5	0.5–1	1–2	2–4	4–8	8-16	16–32	32–64
		(mm)								
		Weight of grain (g)								
Dry land soil	110	31.5^{a}	28.5^{b}	14.3^{c}	46.5^{d}	56.2^{e}	94.4^{f}	173.7^{g}	210.2^{h}	0^{i}
	100	45.9	42.2	21.7	76.8	85.4	116.2	103.1	367.8	0
	90	99.6	88.2	34.7	115.8	106.8	132	122.3	428.8	308.9
	80	380.5	323.9	129.5	478.8	266.9	195.5	120.9	220.2	0
	70	688.4	506.9	166.8	789.4	319.6	104	78.8	0	0
Paddy soil	110	13.1	16.8	8.3	32.3	29.5	49.8	25.6	56.8	0
	100	36.2	39.2	19.3	62.6	52	53.9	54.3	88	0
	90	172.1	180.2	87.6	284.5	190.6	84.7	81.8	53.4	0
	80	361.6	373.6	151.2	580.9	301.8	97.5	73.2	33.4	0
	70	352.5	400.1	146.7	677.2	259.3	84.4	45.1	0	0

a ,b, c, d, e, f, g, h, i – value on the same row with different superscripts differ ($P < 0.05$)

Mass fractal Dimensions (D_m) and Specific surface area ($A_{specific}$)

The highest D_m values were found at 70%W_{SL}, while the lowest fractal dimensions were found at 110% W_{SL} in both dry land and paddy soils. D_m found at 110%, 100%, 90%, 80% and 70% W_{SL} were 2.377, 2.406, 2.49, 2.631 and 2.70 respectively in dry land soil and 2.395, 2.482, 2.584, 2.623 and 2.624 respectively in paddy soil (Figure 4). The D_m of paddy soil was higher when compared to the dry land soil at 110%, 100% and 90%, whilst at 80% and 70% were lower in paddy soil than dry land soil.

$A_{specific}$ increased from 2539.41 to 9106.15 m^2m^{-3} and 3764.55 to 8905.88 m^2m^{-3} as moisture content decreased from 110% to 70% W_{SL} for dry land and paddy soils respectively. $A_{specific}$ produced in paddy soil was much higher than that of dry land soil at 110% to 80% W_{SL}, whilst at 70% W_{SL}; it was slightly higher in dry land soil (Figure 5). It was also observed that $A_{specific}$ up to 90% W_{SL} in dry land soil was much lower, and then there was a sudden jump between 90% and 80% W_{SL}.

Optimum moisture content for seedbed

At 110% W_{SL} the proportion of large aggregates (8–64 mm) was greatest and the proportion of small aggregates (< 0.5 mm) was lowest in both dry land and paddy soils. At 100% W_{SL} the proportion of large aggregates decreased slightly from 72.99 to 68.34% in dry land soil and from 56.93 to 48.38% in paddy soil respectively, whilst the medium aggregates increased slightly from 22.2 to 26.32% and 37.42 to 42.69% and small aggregates from 4.81 to 5.34% and 5.64 to 8.93% in dry land and paddy soils respectively. A similar trend was observed for all moisture contents. However at 70% the proportion of large aggregates decreased to 6.89% in dry land soil and 6.59% in paddy soil respectively, whilst the medium aggregates increased to 67.17% and 75.47% and small aggregates to 25.94% and 17.94% in dry land and paddy soils respectively as shown in Figure 6. The optimum moisture content for seedbed was observed at 80% W_{SL} for dry land soil and 90% W_{SL} for paddy soil.

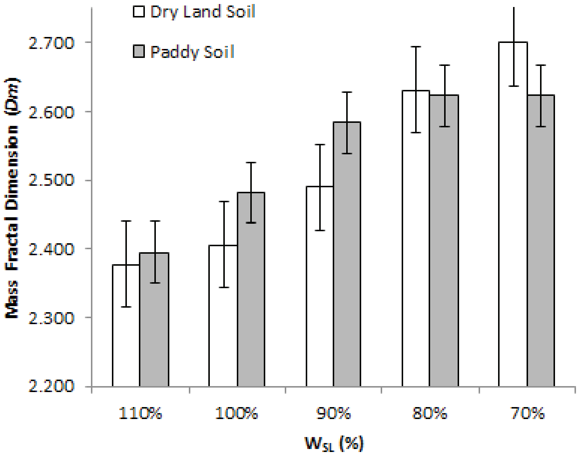

Fig. 4 The fractal dimensions (D_m) produced at various moisture contents near the sticky limit of dry land and paddy soils (W_{SL})

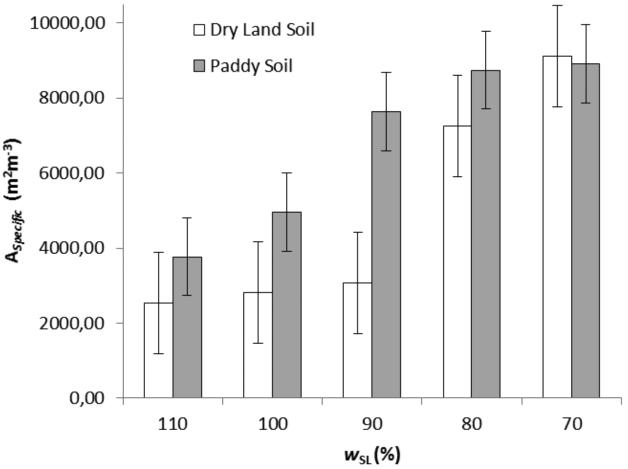

Fig. 5 Specific surface area ($A_{specific}$) produced at various moisture contents the near sticky limit of dry land and paddy soils (W_{SL})

Discussion

The highest D_m values were found at 70% W_{SL} and the lowest at 110% W_{SL}. As the soil moisture content decreases from 110% W_{SL} to 70% W_{SL} the value of D_m increased in both dry land and paddy soils. This is consistent with Perfect and Kay (1991), Martinez-Mena et al. (1999), and Millan et al. (2002), who concluded that the value of D_m increased with increasing fragmentation and higher fractal dimension values, indicating a distribution dominated by smaller fragments. The D_m values were higher at 110%, 100% and 90% W_{SL} in paddy soil than that of dry land soil, whilst lower at 80% and 70% W_{SL} in paddy soil when compared to dry land soil. This is possible because the proportion of aggregates in the < 0.5 mm size range were greater at 110% to 90%, whereas at 80% and 70% the proportion of aggregates in the > 1mm size range was greater in paddy soil. This is consistent with Gulser (2006), who concluded that fractal dimension values decreased with increasing numbers of macro aggregates (> 1 mm). Similarly $A_{specific}$ increased with the decrease in moisture content from 110% to 70% in both dry land and paddy soils. This is in agreement with Keller et al. (2007), with Dexter (2004) and Dexter and Birkás (2004), who concluded that $A_{specific}$ increases with the increase in the proportion of small aggregates. $A_{specific}$ produced in paddy soil was much higher than that of dry land soil at 110% to 80% W_{SL}, whilst at 70% W_{SL} with it was slightly higher in dry land soil. This is attributed to the greater proportion of aggregates in 0.25–2 mm size ranges in paddy soil than dry land soil. It was also observed that $A_{specific}$ up to 90% W_{SL} in dry land soil was much lower, and then there was a sudden jump between 90% and 80% W_{SL}, possibly because there was an abrupt increase in the proportion of aggregates in 0.25–2 mm size ranges at 80% W_{SL} in dry land soil.

According to Braunack and Dexter (1989) the optimal seedbed is produced by 0.5–8 mm aggregates. However, care must be exercised not to use aggregates in the size range of < 0.5 mm and > 8.0 mm as this would result in undesirable physical conditions. Indeed, Berntsen and Berre (1993) revealed that an optimal seedbed for cereals is characterized by about 50% of the aggregates by weight in the 0.5–6 mm fraction. Therefore we divided the entire sieve size ranges into three main size ranges i.e., large aggregates or clods (8–64 mm), medium or desirable (0.5–8 mm) and small (< 0.5 mm). The optimum moisture content is the moisture content at which tillage produces more than 50% of medium size aggregates (0.5–8 mm) and the least proportion of small (< 0.5 mm) as well as large (> 8 mm) aggregates. Hence the optimum moisture content for seedbed was observed at 80% W_{SL} for dry land soil and 90% W_{SL} for paddy soil. At these moisture contents the proportion of medium or desirable aggregates (0.5–8 mm) was greater (56.66%, 65.46%), whilst the proportion of small (17.98%, 15.16%) and large aggregates (25.36%, 19.38%) was lower for both dry land and paddy soils, respectively. Although the greatest proportion of medium-sized (desirable) aggregates was obtained at 70% W_{SL}, the proportion of small aggregates (< 0.5 mm) was also greatest, which was not desirable for good seedbed. This is consistent with Hamblin (1987) and Adam and Erbach (1992), as they found that the greatest proportion of very fine soil aggregates and large clods in the seedbed can cause poor seed germination, and delayed seedling emergence. The op-

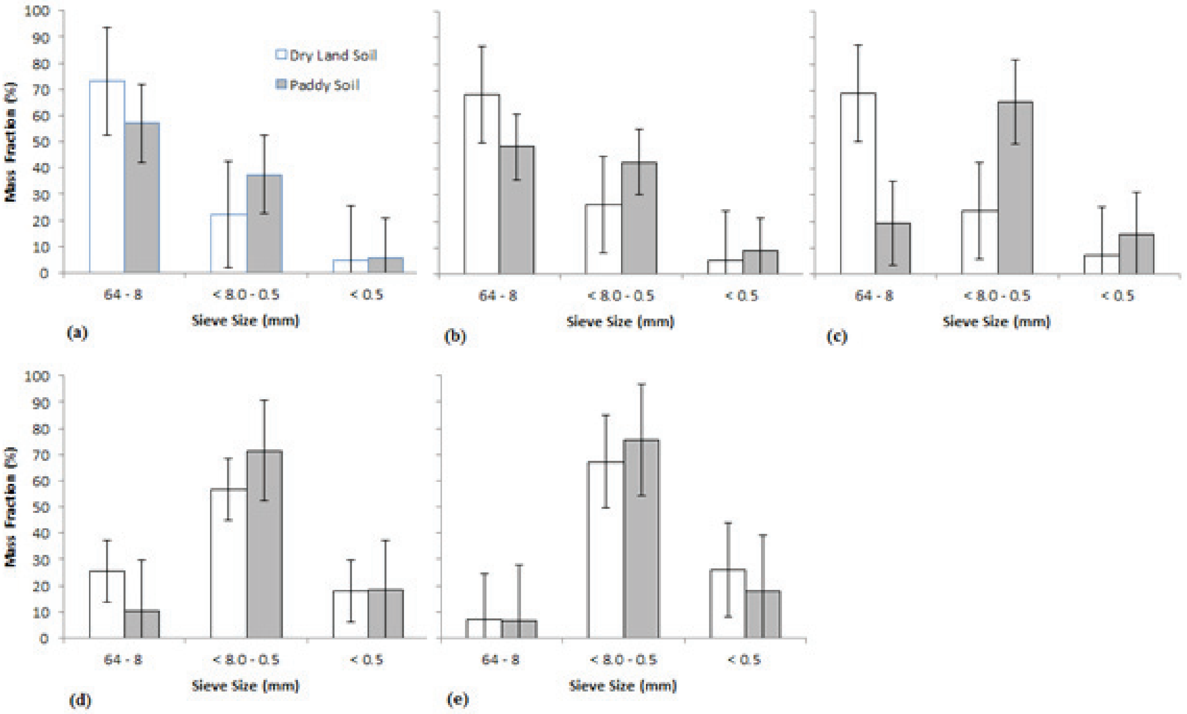

Fig. 6 Mass fraction (%) in different sieve size ranges for dry land soil and paddy soil: (a) 110% of the sticky limit, (b) 100% of the sticky limit, (c) 90% of the sticky limit, (d) 80% of the sticky limit, and (e) 70% of the sticky limit

timal growth occurs in the presence of soil structural units > 0.5 mm (Nash and Baligar, 1974).

These findings are supported by Braunack (1995) who described an earlier and greater emergence of maize seedlings when planted in fine (aggregate size between 1 and 2 mm) vs. coarse (aggregate size between 5 and 15 mm) seedbeds. Also Jaggi et al. (1972) concluded that a seedbed of 1–2 mm aggregates with a dry bulk density of 1.2–1.3 g cm^{-3} would give the best wheat grain yield on a clay soil. With larger aggregate sizes restriction of water movement to the roots may limit plant growth. In a study by Braunack and Dexter (1989) maximum wheat yields were reported with seedbeds of 2–3 mm aggregates. This is also consistent with Braunack and Dexter (1988), who attributed that intermediate size aggregates (2–3 mm) resulted in earlier emergence and higher wheat yields than with larger aggregates (> 4mm) on a loam soil. Finer aggregates (< 1 mm) tend to restrict aeration and reduce seed emergence. Moreover Nash and Baligar (1974) concluded that soybean emergence was delayed in the presence of structural units < 1 mm and > 4 mm.

In this study, optimum moisture content for dry land soil was 12% and 15.9% for paddy soil. This difference is possible because the paddy soil has a higher organic matter content, lower bulk density and a slightly different texture than the dry land soil, although the textural class of both soils was the same. The optimum moisture content is not constant, but may be different for (i) different soils and (ii) the same soil at different bulk densities (Keller et al., 2007). The results presented here are consistent with De la Rosa et al. (2009) who demonstrated that soils of the Campiña site at São Paulo in Brazil (SE03: Typic Chromoxerert) and Marismas (SE05: Salorthidic Fluvaquent) have optimum moisture content < 15% moisture content. Ahmadi and Mollazade (2009) found that in the silty clay loam soil and loam soil the best soil moisture content for tillage are 15–18 and 13–15%, respectively. Ojeniyi and Dexter (1979) indicated that the greatest total macro porosity was produced in the range of moisture contents 12.6 to 18.3% on an Urrbrae loam soil (17% clay, 32 % silt and 51% sand). Moreover, De Toro and Arvidsson (2003) found the highest fraction of fine aggregates at an average seedbed moisture content of 150 g kg^{-1} or lower, which is about 50% of the moisture content at the plastic limit for this soil. This value is much lower than what is generally found in the literature as the optimum moisture content for seedbed. Dexter (1979) stated that in addition to soil moisture content, soil structures produced by tillage (on different soils) depend on many factors, including soil texture, soil management and soil compaction.

Conclusions

Upon completion of this study it was found that the maximum friability occurred at 70% W_{SL} and the lowest at the 110% W_{SL}. The optimum moisture content for seedbed was near (close to) the sticky limit of both dry land and paddy soils. The main conclusions drawn from the study are as follows:

In both dry land and paddy soils:

the highest D_m values were found at 70% W_{SL}, whilst the lowest fractal dimensions were found at 110% W_{SL}.

the highest $A_{specific}$ was found at 70%W_{SL}, whilst the lowest was found at 110% W_{SL}.

The optimum moisture content for seedbed was observed at 80% W_{SL} for dry land soil and 90% W_{SL} for paddy soil.

Acknowledgements

The work was sponsored by the National *Natural* Science Foundation of China (Grant Nos. 51275250; 41371238) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

Adam, K. M. and D. C. Erbach, 1992. Secondary tillage tool effect on soil aggregation. *Transactions of the American Society of Agricultural Engineers,* **35** (6): 1771–1776.

Adamu, G. K. and A. K. Aliyu, 2012. Determination of the Influence of Texture and Organic Matter on Soil Water Holding Capacity in and Around Tomas Irrigation Scheme, Dambatta Local Government Kano State. *Research Journal of Environmental and Earth Sciences,* **4** (12): 1038–1044.

Ahmadi, H. and K. Mollazade, 2009. Effect of Plowing Depth and Soil Moisture Content on Reduced Secondary Tillage. *Agricultural Engineering International: The CIGR EJournal* Manuscript MES 1195, Vol. XI.

Aluko, O. B. and D. A. Seig, 2000. An experimental investigation of the characteristics of and conditions for brittle failure in two-dimensional soil cutting. *Soil & Tillage Research*, **57**: 143–157.

Atkinson, B. S., 2008. Identification of optimum seedbed preparation and establishment using soil structural visualization. PhD Dissertation, *University of Nottingham.*

Baruah, T. C. and H. P. Barthakur, 1997. A Text Book of Soil Analysis, *Vikas Publishing House*, New Delhi.

Barzegar, A. R., Hashemi, A. M., S. J. Herbert and M. A. Asoodar, 2004. Interactive effects of tillage system and soil water content on aggregate size distribution for seedbed preparation in Fluvisols in southwest Iran. *Soil & Tillage Research*, **78**: 45–52.

Baver, L. D., W. H. Gardner and W. R. Gardner, 1972. Soil Physics. *John Wiley and Sons*, New York.

Berntsen, R. and B. Berre, 1993. Fracturing of soil clods and the soil crumbling effectiveness of draught tillage implements. *Soil & Tillage Research,* **28**: 79–94.

DOI: 10.1016/0167-1987(93)90057-V

Blake, G. R. and K. H. Hartge, 1986. Bulk density. In: A. Klute (ed.) Methods of Soil Analysis, Part 1 Physical and Mineralogical Method, *Society of Agronomy and Soil Science Society of America*, Madiso, pp. 363–376.

Bouyoucos, G. J. 1927. The hydrometer as a new method for the mechanical analysis of soils. *Soil Science.* **23** (5): 343–353.

Braunack, M. V., 1995. Effect of aggregate size and soil water content on emergence of soybean (*Glycine max* L. Merr.) and maize (*Zea mays* L.). *Soil & Tillage Research,* **33**: 149-161.

Braunack, M. V. and A. R. Dexter, 1988. The effect of aggregate size in the seedbed on surface crusting and growth of yield of wheat (*Triticum eastivum*, L. cv. Halberd) under dry land conditions. *Soil & Tillage Research,* **11**: 133–145.

Braunack, M. V. and A. R. Dexter, 1989. Soil aggregation in the seedbed: A review. II. Effect of aggregate sizes on plant growth. *Soil & Tillage Research,* **14**: 281–298.
DOI: 10.1016/0167-1987(89)90014-7

Braunack, M. V., J. S. Hewitt and A. R. Dexter, 1979. Brittle fracture of soil aggregates and the compaction of aggregate beds. *Journal of Soil Science,* **30**: 653–667.

Brown, A. D., A. R. Dexter, W. C. T. Chamen and G. Spoor, 1996. Effect of macroporosity and aggregate size on seed–soil contact. *Soil & Tillage Research*, **38**: 203–216.

Campbell, D. J., 2001. Liquid and plastic limits, In: K. A. Smith and C. Mullins (eds.), Soil and Environmental Analysis: Physical Methods, *Marcel Dekker, Inc.,* New York, pp. 349–376.

Chandler, H. W., 1984. The use of non-linear fracture mechanics to study the fracture properties of soils. *Journal of Agricultural Engineering Research,* **29**: 321–327.

De la Rosa, D., M. Anaya-Romero, E. Diaz-Pereira, N. Heredia and F. Shahbazi, 2009. Soil specific agro-ecological strategies for sustainable land use –A case study by using MicroLEIS DSS in Sevilla Province (Spain). *Land Use Policy,* **26**: 1055–1065.

De Toro, A. and J. Arvidsson, 2003. Influence of spring preparation date and soil water content on seedbed physical conditions of a clayey soil in Sweden. *Soil & Tillage Research,* **70**: 141–151.

Dexter, A. R., 1979. Prediction of soil structures produced by tillage. *Journal of Terramechanics*, **16**: 117–127.

Dexter, A. R., 1988. Advances in characterization of soil structure. *Soil & Tillage Research,* **11**: 199–238.

Dexter, A. R., 2004. Soil physical quality. Part II. Friability, tillage, tilth and hard-setting. *Geoderma,* **120**: 215–225.

Dexter, A. R. and N. R. A. Bird, 2001. Methods for predicting the optimum and the range of water contents for tillage based on the water retention curve. *Soil & Tillage Research,* **57**: 203–212.

Dexter, A. R. and M. Birkas, 2004. Prediction of soil structures produced by tillage. *Soil &Tillage Research*, **79**: 233–238.

Dexter, A. R. and G. Richard, 2009. Tillage of soils in relation to their bi-modal pore size distribution. *Soil & Tillage Research*, **103**: 113–118.

Dexter, A. R. and C. W. Watts, 2000. Tensile strength and friability. In: K. A. Smith and C. E. Mullins (ed.) Soil and Environmental Analysis Physical Methods, *Marcel Dekker Inc*, New York. pp. 405–433.

Diaz-Zorita, M., E. Perfect and J. H. Grove, 2002. Disruptive methods for assessing soil structure. *Soil & Tillage Research*, **64**: 3–22.

Dürr, C. and J. Aubertot, 2000. Emergence of seedlings of sugar beet (*Beta vulgaris* L.) as affected by size, roughness and position of aggregates in the seedbed. *Plant Soil,* **219**: 211–220.

Fredlund, D. G. and S. K. Vanapalli, 2002. Shear strength of unsaturated soils. In: J. H. Dane and G. C. Topp, (Eds.) Methods of Soil Analysis: Part 4. Physical Methods, *Soil Science Society of America Book Series*, No. 5, Madison, pp. 329–361.

Guerif, J., G. Richard, C. Durr, J. M. Machet, S. Recous and J. Roger–Estrade, 2001. A review of tillage effects on crop residue management, seedbed conditions and seedling establishment. *Soil & Tillage Research,* **61**: 13–32.

Hadas, A., 1997. Soil tilth – the desired soil structural state obtained through proper soil fragmentation and reorientation processes. *Soil & Tillage Research,* **43**: 7–40.

Hadas, A. and D. Wolf, 1983. Energy efficiency in tilling dry clod forming soils. *Soil & Tillage Research*, **3**: 47–59.

Hakansson, I., A. Myrbeck and A. Etana, 2002. A review of research on seedbed preparation for small grains in Sweden. *Soil & Tillage Research*, **64** (1–2): 23–40.

Hakansson, I. and J. Von Polgar, 1984. Experiments on the effects of seedbed characteristics on seedling emergence in a dry weather situation. *Soil & Tillage Research*, **4**: 115–135.

Hallett, P. D., A. R. Dexter and J. P. K. Seville, 1995. Identification of pre-existing cracks on soil fracture surfaces using dye. *Soil & Tillage Research,* **33**: 163–184.

Hamblin, A. P., 1987. The effect of tillage on soil physical conditions, In: P. S. Cornish and J. E. Pratley (Eds.), Tillage: New Directions for Australian Agriculture, *Inkata Press*, Sydney, pp. 128–170.

Hatibu, N., 1987. The mechanical behaviour of brittle agricultural soils. Ph.D. Dissertation. *University of Newcastle upon Tyne*, Newcastle upon Tyne, UK.

Jaggi, I. K., S. M. Gorantiwar and S. S. Rhanna, 1972. Effect of bulk density and aggregate size on wheat growth. *Journal of Indian Society of Soil Science,* **20**: 421–423.

Keller, T., J. Arvidsson and A. R. Dexter, 2007. Soil structures produced by tillage as affected by soil water content and the physical quality of soil. *Soil & Tillage Research.* **92**: 45–92.

Lal, R. and M. K. Shukla, 2004. Principles of Soil Physics. *Marcel Dekker*, New York.

Makanga, J.T., Salokhe, V.M. and Gee-Clough, D. 1996. Effect of tine rake angle and aspect ratio on soil failure patterns in dry loam soil. *Journal of Terramechanics*. **33**(5): 233–252.
doi: 10.1016/S0022-4898(97)00007-4

Makanga, J. T., V. M. Salokhe and D. Gee-Clough, 2010. Deformation and force characteristics caused by inclined tines in loam soil with moisture content below liquid limit. *Journal of Agriculture, Science and Technology*. **12** (2): 181–205.
http://elearning.jkuat.ac.ke/journals/ojs/index.php/jagst/article/view/19 (Seen 29 April 2013)

Mosaddeghi, M. R., M. Morshedizad, Mahboubi, A. R. Dexter

and R. Schulin, 2009. Laboratory evaluation of a model for soil crumbling for prediction of the optimum soil water content for tillage. *Soil & Tillage Research*, **105**: 242–250.

Mueller, L., U. Schindler, N. R. Fausey and R. Lal, 2003. Comparison of methods for estimating maximum soil water content for optimum workability. *Soil & Tillage Research,* **72**: 9–20.

Muller, L., J. Lipiec, T. S. Kornecki and S. Gebhardt, 2011. Trafficability and workability. In: J. Gliński, J. Horabik and J. Lipiec (Eds.) Encyclopedia of Agrophysics, *Springer*, Netherlands, pp. 912–924.
DOI 10.1007/978-90-481-3585-1

Munkholm, L. J., 2002. Soil fragmentation and friability. Effects of soil water and soil management. Ph.D. Thesis, *Danish Institute of Agricultural Sciences*, Department of Crop Physiology and Soil Science.

Nalavade, P. P., V. M. Salokhe, T. Niyamapa and P. Soni, 2010. Performance of free rolling and powered tillage discs. *Soil & Tillage Research*. **109** (2): 87–93.
doi: 10.1016/j.still.2010.05.004

Nash, V. E. and V. C. Baligar, 1974. The growth of soybean (*Glycine*) In: D. L. Smith and C. Hamel (Eds.) Crop Yield Physiology and Pro*max* Roots in Relation to Soil Micromorphology. *Plant Soil*. **41**: 81–89.

Nasr, H. M. and F. Selles, 1995. Seedling emergence as influenced by aggregate size, bulk density, and penetration resistance of the seedbed. *Soil Tillage Res.,* **34**: 61–76.

Ojeniyi, S. O. and A. R. Dexter, 1979. Soil factors affecting the macrostructures produced by tillage. *Transactions of the American Society of Agricultural Engineers,* **22**: 339-343.

Perfect, E., M. Diaz-Zorita and J. H. Grove, 2002. A prefractal model for predicting soil fragment-size distributions. *Soil & Tillage Research,* **64**: 79–90.

Rajaram, G. and D. C. Erbach, 1998. Drying stress effect on mechanical behaviour of a clay-loam soil. *Soil & Tillage Research,* **49**: 147–158.

Russell, E. W., 1973. Soil Conditions and Plant Growth, 10th ed., *Longmans*, London, 849 pp.

SPSS, Inc., 2007. SYSTAT version 16.0: Statistics, Chicago, Illinois

Utomo, W. H. and A. R. Dexter, 1981. Effect of ageing on compression resistance and water stability of soil aggregates disturbed by tillage. *Soil & Tillage Research*, **1**: 127–137.

Wagner, L. E., N. M. Ambe and P. Barnes, 1992. Tillage-induced soil aggregate status as influenced by water content. *Transactions of the American Society of Agricultural Engineers,* **35**: 499–504.

Walkley, A. and I. A. Black, 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. *Soil Science*, **37**: 29–37.

Watts, C. W. and A. R. Dexter, 1998. Soil friability: Theory, measurement and the effects of management and organic carbon content. *European Journal of Soil Science*, **49**: 73–84.

Received November, 23, 2015; accepted for printing June, 17, 2016