Rice lands of South and South East Asia – Some soil physical aspects

R.M. Bhagat
Department of Soil Science, CSKHPAU, Palampur-176062, H.P. INDIA

Worldwide about 148 million ha are planted to rice (Oryza sativa L.) each year, taking into account double and triple cropping. About 90 per cent of this area is in Asia and two thirds in South and South-East Asia, where rice is the most dominant crop grown during the wet season. When wetland rice is included in a cropping system, the soils undergo unique changes in physical properties (Bhagat et al, 1996). Wet tillage or puddling has become synonymous with wetland rice culture and it refers to the destruction of aggregated condition of the soil by mechanical manipulation within a narrow range of moisture contents above and below field capacity (0.03 MPa), so that soil aggregates lose their identity and the soil is converted into a structurally more or less homogenous mass of ultimate particles. During puddling, soils are subjected to two kinds of deforming stresses: (a) the normal stress (load) associated with compression and (b) tangential stress causing shear. The compression is more effective below the upper plastic limit (moisture content at which the soil-water system can flow as a sticky fluid paste); shearing effects dominate above the upper plastic limit. The work done in puddling can be represented by the following relation:

$$W = -\int_{Vi(c)}^{Vf(c)} P\,dv - \int_{Vf(c)}^{Vz} P\,dv + 1/M_s \int_{\theta_0}^{\theta_z} T\,d\theta$$

Total work done in = puddling	Work done by normal stress - before shear	Work done by normal stress + during shear	Work done by tangential stress during shear

Where P is the normal stress, M_s is the mass of dry soil, T is the torque, θ is the angular rotation of a piston, v is the apparent specific volume, Vi(c) is the initial specific volume at the beginning of normal stress, Vf(c) is the final specific volume due to normal stress, V_z is the terminal value due to shear, θ_0 is the zero angular displacement of a piston, and θ_z is the final displacement of a piston.

Puddling or wet tillage coupled with submerged conditions are responsible for making drastic effects on soil physical characteristics of rice soils. These effects can be continue either for short time or long time. During rice-rice or rice-wheat cropping sequence the system undergoes transition from saturated to unsaturated conditions. While this happens, the soil physical properties again undergo changes. The following discussion shows how the physical characteristics of the whole soil system behave:

Soil structure

Puddling destroys and coverts aggregates and peds into plastic mud. When an initially dry soil is wetted, there is uneven swelling of aggregates, which subsequently explode due to entrapped air resulting in aggregates slaking. Continuous wet tillage (repeated plowings and harrowings) converts the soil into a plastic mud with massive structure. While the puddled layer is not uniform, a drop in mean weight diameter has been observed. In the puddle layer, clay particles are oriented in parallel rows and are surrounded by water saturated capillary pores. The soil matrix therefore exhibits a two phase system i.e. solid and liquid, the gaseous phase is either missing or some air is entrapped in storage and residual pores. The practice of lowland rice-rice system in some parts of South and South East Asia has made the soils excessively soft due to puddling season after season resulting in a progressive deterioration in soil structure. In fact these soils do not get time to rejuvenate by way of renewal of soil aeration.

In a long term study on lowland rice carried out in north-western India (Table 1), it was observed that immediately after lowland rice harvest water stable aggregates (WSA)> 0.25 mm as well as the mean weight diameter (MWD) were lower in puddled plots compared to the non puddle plots (Bhagat et al., 1994). Long term addition of residue at 30 t ha^{-1}, although increased both the WSA and MWD of puddled plots, but the trend remained the same. In a six years study of a lowland- rice and upland-wheat system (Table 3), WSA>0.25 and MWD determined after six rice crops were significantly lower in a continuously puddled silty clay loam soil (Sharma et al., 1995). Addition of residues although improve aggregation status of this soil.

Bulk density and soil strength

Puddling effects on bulk density are dependent on the aggregation status of the soil before puddling. If a parallel oriented, closely packed structure is produced from a well aggregated open structure, bulk density would increase. The strong inter-particle forces favor well oriented structure, while weak inter-particle forces favor an open gel structure. Initial submergence before tillage (a practice in many parts of Asia) also decreases bulk density. Bulk density increases when the puddled soils undergo desiccation in a lowland-upland (e.g. rice-wheat) situation because of soil shrinkage.

During lowland rice growth (Table 2), bulk density significantly decreased under puddled plots compared to non puddled plots (Bhagat et al. 1999a). However, when the lowland system made a transition to upland system, significant increase in bulk density was observed (Table 1) when no residues were added (Bhagat et al., 1994).

The puddle soils become very hard upon drying and progressively develop polygonal cracks, whose width and depth increases with time, depending upon the nature and type of clay and the moisture regime. The crack spacing depends on the ability of the soil to deform under tensile stresses, which are generated parallel to the soil surface, when the puddled soil dries and shrinks. The cracked soils dry very quickly, because of development of the secondary planes of evaporation at the exposed edges. The open cracked hard soils are difficult to till and upon tillage brings out large clods (big lumps of soil weighing from few grams to few kilograms). These clods have high clod breaking strength (CBS) and require large amount of energy to break them to prepare a fine seed bed (for a proper seed-soil contact for germination). Sharma et al. (1995) have found out that a puddle soil without residues had the highest CBS compared to the puddle soils with residues (Table 3). In the same study the non puddled soil (data not shown) had lower

CBS compared to the puddle soil. On the other hand, when a hard desiccated soil is puddle under wet condition, it brings the soil particles back into the suspension and lowers the bulk density. The bulk density, however, may increase when the soil is still submerged, due to settling of particles. The particles may settle and consolidate because of self flocculation of dispersed clay, depending possibly on soil texture and type of clay. Settling is faster in sandy soils with kaolinitic mineralogy.

The soil strength is a measure of resistance that must be overcome to cause penetration/deformation in soil. This resistance is to both volumetric compression and linear deformation, which depends on moisture content, texture, type and amount of clay and the arrangements of particles in the soil matrix. The soil strength falls rapidly with increase in moisture content and increases with an increase in bulk density. The very high moisture content and a fairly loose arrangement of soil particles in the puddle layer may bring the soil strength to near zero. However when the puddle soils dry out soil penetration resistance increases rapidly, as bulk density increases. Figure 1 shows lower penetration resistance in non puddled plots compared to puddled plots in a desiccating soil of northern India (Bhagat et al., 1994). Although the soil penetration can be rapidly measured with a penetronmeter, the readings need careful interpretation because a wide combination of soil properties may give rise to the same values.

The pore space

Change in the orientation of soil particles in puddled layer brings about changes in soil porosity. The parallel oriented structure produced following puddling from an initially open gel structure, total porosity will decrease. Total pore volume may, however, temporarily increase upon puddling. But an ultimate decline in total porosity is noticed upon puddling in many studies (Bhagat, 1990; Sharma and Bhagat, 1993; Bhagat et al., 1994). Bhagat et al (1999a), in study on tillage effects on lowland rice observed that puddling decreased drainage pores and increased water retention pores. The pore size distribution also undergoes major changes upon puddling. Sharma and Bhagat (1993) have found out that puddling decreased water transmission pores from 14.6 to 10.9 per cent in loamy sand, 10.2 to6.8 per cent in silt loam, 23.2 to7.3 per cent in loam and 17.6 to 4.9 per cent in clay loam. The depth of puddling further influences the total porosity in the soil to deeper depths, therby affecting the water flux through the soil. The results of the studies carried out by Sharma and Bhagat (1993) indicated that flux was a negative power function of puddling depth. About 95 percent reduction in water flux due to per unit increase in puddling depth was explained by the linear function of clay content, whereas the relative water flux was an exponential function of clay content (Fig. 2). The measurement of porosity of puddled soils should be carefully made, because the capillary rise equation normally used for rigid porous system is difficult to apply in non-rigid, swollen system, which deflates (shrinks) when the moisture loss occurs.

Changes in pore space (pore size distribution) upon puddling effects other soil physical properties like the aeration status, the retention-transmission characteristics and evaporation losses of soils.

Water retention and transmission characteristics

Depending upon the soil texture and the initial aggregation status at low soil water potential (more negative), water retention in puddled soils is always higher then the non puddle soil. In a long term study on rice straw management in lowland rice - upland wheat system, Bhagat and Verma (1991) observed that water retention was always higher in plots which were puddle in a previous rice compared to the non puddle plots, even if these were supplied with straw mulch or farm yard manure in the following upland wheat crop (Fig 3). Normally the available water capacity (defined as per the classical concept to be $\psi_{0.01MPa}$ - $\psi_{1.5\ MPa}$) of puddled soil is higher than the non puddle soil. However, when the submerged puddle soils revert back to upland non puddle condition, its water retention falls. Resaturation of such soils may not necessarily restore the soils original water retention capacity. Close packing of soil particles in parallel orientation in puddle soils reduces their saturated hydraulic conductivity and percolation losses in submerged puddled rice fields. Continuous inclusion of lowland puddled rice in a cropping sequence year after year results in the development of hard subsurface layers, which act as a hydraulic barrier and impede water movement. However, the puddling effects on water transmission characteristics vary widely with soil type, intensity of puddling, and the type of the implement used. Percolation rates have been found to fall rapidly with the increase in intensity of puddling in several soils. In a study carried out in Central Luzon, Philippines (Table 4), it was observed that increased tillage intensity (repeated puddling) in lowland rice significantly decreased percolation +seepage compared to less intensive tillage (Bhagat et al., 1999b).

The thermal regime

Wet tillage (puddling) in rice soils affects the thermal regime by changing soil properties, such as bulk density, moisture regime and the transmission characteristics. Thermal conductivity (k) and the volumetric heat capacity (c) increase with bulk density and moisture content, because the k and c of soil particles and water are much higher than those of air. Thermal diffusivity (k/c), which denotes the temperature changes in any part of soil, also increases with increasing moisture content to about-0.1 MPa water potential and then it falls, because above -0.1 MPa water potential, c increases much faster then k. Increase in percolation rates may increase or decrease soil temperature depending on irrigation water temperature and solar radiation received.

Thermal regimes of air, flood water and soil monitored for diurnal variations in temperature, indicated that for flood water as well as soil, the puddled plots always maintained a higher temperature compared to non puddle plots. (Bhagat et al, 1994). Increase in temperature following puddling is attributed to a decrease in percolation rates. In puddled plots water continue to pond on the surface for longer periods compared to non puddled plots resulting in an increase in temperature.

References

Bhagat, R.M. 1990. Effect of tillage and residue management on hydro-thermal regime, nutrient uptake and yield of wheat in a river deposit. *Soil Tillage Res*. 17: 315-326.

Bhagat, R.M. and Verma, T.S. 1991. Impact of rice straw management on soil physical properties and wheat yield. *Soil Sci*. 152: 108-115.

Bhagat, R.M., Sharma, P.K. and Verma, T.S. 1994. Tillage and residue management effects on soil physical properties and rice yield in north- western Himalayan soils. *Soil Tillage Res*. 29: 323-334.

Bhagat, R.M., Bhuiyan, S.I. and Moody, K. 1996. Water, tillage and weed interactions in lowland tropical rice: A review. *Agril Water Mgt*.31: 165-184.

Bhagat, R.M., Mangotra, M. and Sharma, Pradeep K (1999a). Tillage effects on soil physical properties and yield of rainfed rice (Oryza sativa L.). *J. Indian Soc. Soil Sci*.47: 415-421

Bhagat, R.M., Bhuiyan, S.I. and Moody, K. 1999b. Water, tillage and weed management options for wet seeded rice in the Philippines. *Soil and Tillage Res*.,52: 51-58

Sharma, P.K. and Bhagat, R.M. 1993. Puddling and compaction effects on water permeability of texturally different soils. *J. Indian soc. Soil Sci*. 41: 1-6.

Sharma, Pradeep K., Verma, T.S. and Bhagat, R.M. 1995. Soil structural improvements with addition of Lantana camara biomass in rice-wheat cropping. *Soil Use and Management*, 11: 199-203.

Table 1. Mean values of water - stable aggregates (WSA) greater than 0.25 mm, mean weight diameter (MWD), bulk density, total porosity and saturated hydraulic conductivity for 0-0.15 m depth under various treatments. *(Bhagat, R.M., Sharma, P.K. and Verma, T.S., 1994)*

Structural indices	**Treatment***						**L.S.D. (0.05)**
	PM_3	CM_3	NPM_3	PM_0	CM_0	NPM_0	
WSA>0.25mm (g(100 g)$^{-1}$)	40.6	39.7	42.7	37.5	38.2	39.0	3.5
MWD (mm)	2.38	2.24	3.01	2.10	2.30	2.27	0.34
Bulk density (Mg m^{-3})	1.37	1.44	1.28	1.55	1.52	1.29	0.14
Total porosity (m^3(100 m)$^{-3}$)	46.8	44.2	50.3	39.9	41.0	50.0	3.7
Saturated Hydraulic conductivity (m s^{-1})	8.33x10^{-7}	7.77x10^{-7}	1.37x10^{-6}	3.88x10^{-7}	3.33x10^{-7}	4.72x10^{-7}	-

*P=Puddling; C=Compaction; NP= Non puddled dry tillage; M_0= No residue; M_3= 30t ha^{-1} residue

Table 2. Soil physical properties at 60 days after seeding for the surface (0-0.15 m) depth in a wet season. *(Bhagat, R.M, Mangotra, M., and Sharma, P.K., 1999)*

Treatment*	Bulk density (Mg m^{-3})	Soil penetration resistance (MPa)	Pore size distribution			Hydraulic conductivity (m s^{-1})
			% of total porosity			
			Drainage pores (>50 ③m)	Water retention pores (0.5-50 ③m)	Residual pores (<0.5 ③m)	
DS	1.01	0.80	14	40	46	4.70x10^{-6}
DS+H	0.89	0.58	6	50	44	1.00x10^{-6}
DS+FYM	0.98	0.69	17	40	43	3.30x10^{-6}
C	1.24	1.05	9	42	49	0.90x10^{-6}
RF	1.10	0.95	14	42	44	3.25x10^{-6}
P+TP	0.95	0.63	4	51	45	1.10x10^{-6}
CD (*p= 0.05*)	0.06	0.18	-	-	-	1.18x10^{-6}

*DS= Dry conventionally tilled plots; DS+H= Dry conventionally tilled plots followed by wet tillage (*Halod*) at 3-4 leaf stage of rice; DS+FYM= Dry conventionally tilled plots supplied with 10 t ha^{-1} farm yard manure; C= Soil compaction; RF= Ridge furrow system; P+TP= Puddling and transplanting

Table 3. Effect of six annual applications of Lantana camara on bulk density of soil, aggregates and clods, water stability of aggregates and clod –breaking strength in a silty clay loam soil under rice-wheat cropping. (Sharma, P.K., Verma, T.S. and Bhagat, R.M., 1995)

Lantana application (t ha^{-1})	Bulk density (t m^{-3})				Water Stable aggregates >0.25 mm (%)	Aggregate porosity (%)	Mean weight diameter (mm)	Clod breaking strength (kPa)
	Soil		Aggregates	Clods				
	0-7.5 cm	7.5-15 cm	(2-8 mm)	4-6 cm				
0	1.42	1.48	1.54	1.49	72.9	38.2	2.66	419.9
10	1.39	1.48	1.50	1.45	79.0	39.8	3.89	377.2
20	1.34	1.46	1.49	1.44	81.9	40.2	4.18	220.8
30	1.31	1.38	1.48	1.40	82.8	40.6	4.09	215.6
L.S.D. ($p \leq 0.05$)	0.05	0.07	0.04	0.03	3.3	1.04	0.67	87.0

Table 4. Changes in Percolation plus seepage during Wet season of 1995 (WS-95) and Dry season of 1996 (DS-96)
(*Bhagat, R.M., Bhuiyan, S.I., and Moody, K. 1999*)

Season	Weeks after planting	Treatments						LSD[f]		ET[g]
		W1[a]T1[b]	W1[a]T2[d]	W2[c]T1[b]	W2[c]T2[d]	W3[e]T1[b]	W3[e]T2[d]	Tillage	Water	
WS-95	2	17.7	17.1	16.9	17.0	10.1	9.4	ns[h]	3.1	4.5
	4	24.0	21.9	18.1	16.4	7.5	6.2	ns[h]	7.8	4.7
	6	20.3	16.7	15.9	16.4	7.7	8.2	1.2	6.1	4.3
	8	16.1	16.9	6.9	9.7	8.4	6.7	1.3	5.9	5.3
	10	11.9	11.4	5.3	5.6	5.1	6.0	ns[h]	5.5	4.4
	12	6.6	4.8	4.5	3.7	2.1	1.7	ns[h]	ns[h]	4.2
	14	1.4	1.1	0.0	0.4	0.1	0.0	ns[h]	ns[h]	5.3
DS-96	2	22.1	21.5	22.0	20.5	16.5	14.2	ns[h]	2.5	5.2
	4	19.7	22.5	22.5	17.6	13.5	12.0	ns[h]	3.2	5.8
	6	21.7	20.4	18.6	16.5	12.4	10.4	1.5	3.1	5.8
	8	17.4	14.6	13.5	12.0	10.6	9.0	1.3	2.1	5.28
	10	12.3	11.4	8.4	7.2	6.2	6.0	ns[h]	ns[h]	4.6
	12	11.5	11.6	5.6	4.5	4.0	2.5	ns[h]	ns[h]	5.1
	14	7.8	5.5	4.6	3.1	3.0	1.8	ns[h]	ns[h]	5.8

[a] Shallow flooding throughout the crop growth; [b] One plowing+two harrowings; [c] Shallow flooding until panicle initiation then saturation; [d] Two plowings+two harrowings; [e] Saturated soil; [f] Least significant difference; [g] Daily transpiration rate; [h] Not significant

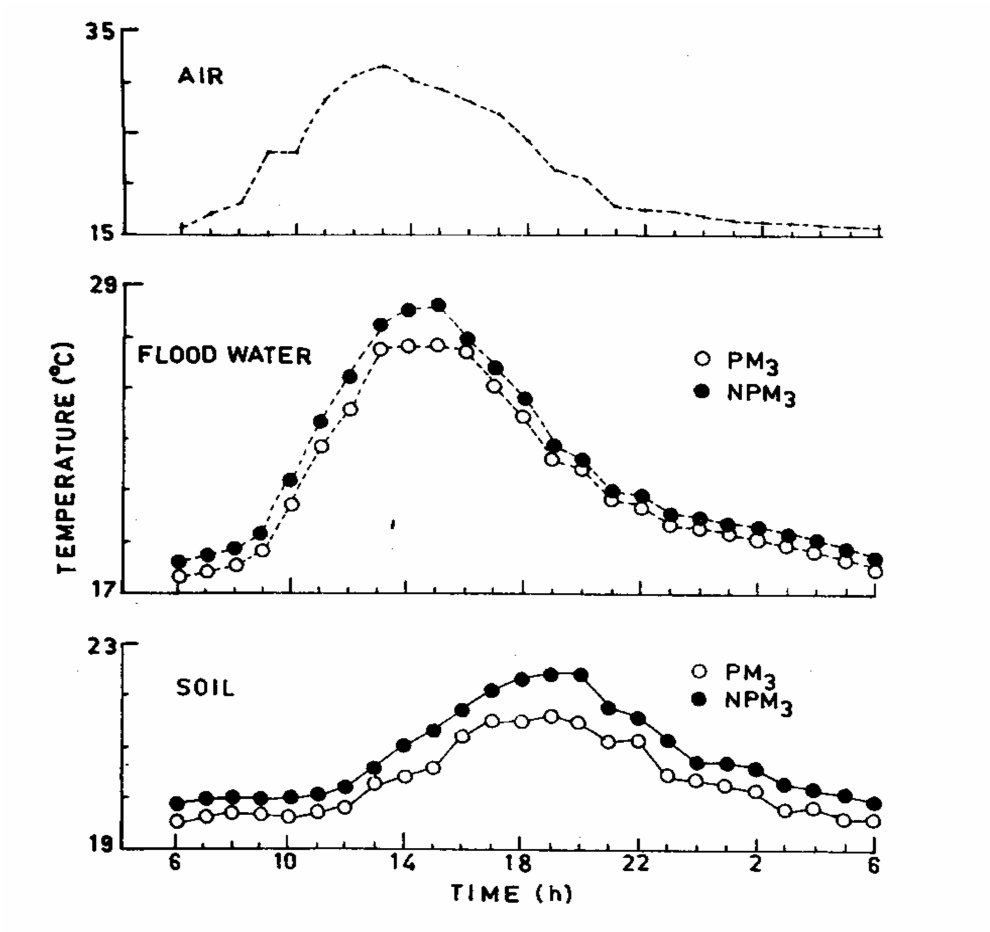

Fig 4. Diurnal temperature fluctuations in air, soil and flood water as affected by puddling and residue incorporation. P= Puddled; NP= Non puddle; M3= 30 tha^{-1}residue addition. (Bhagat et al., 1994)

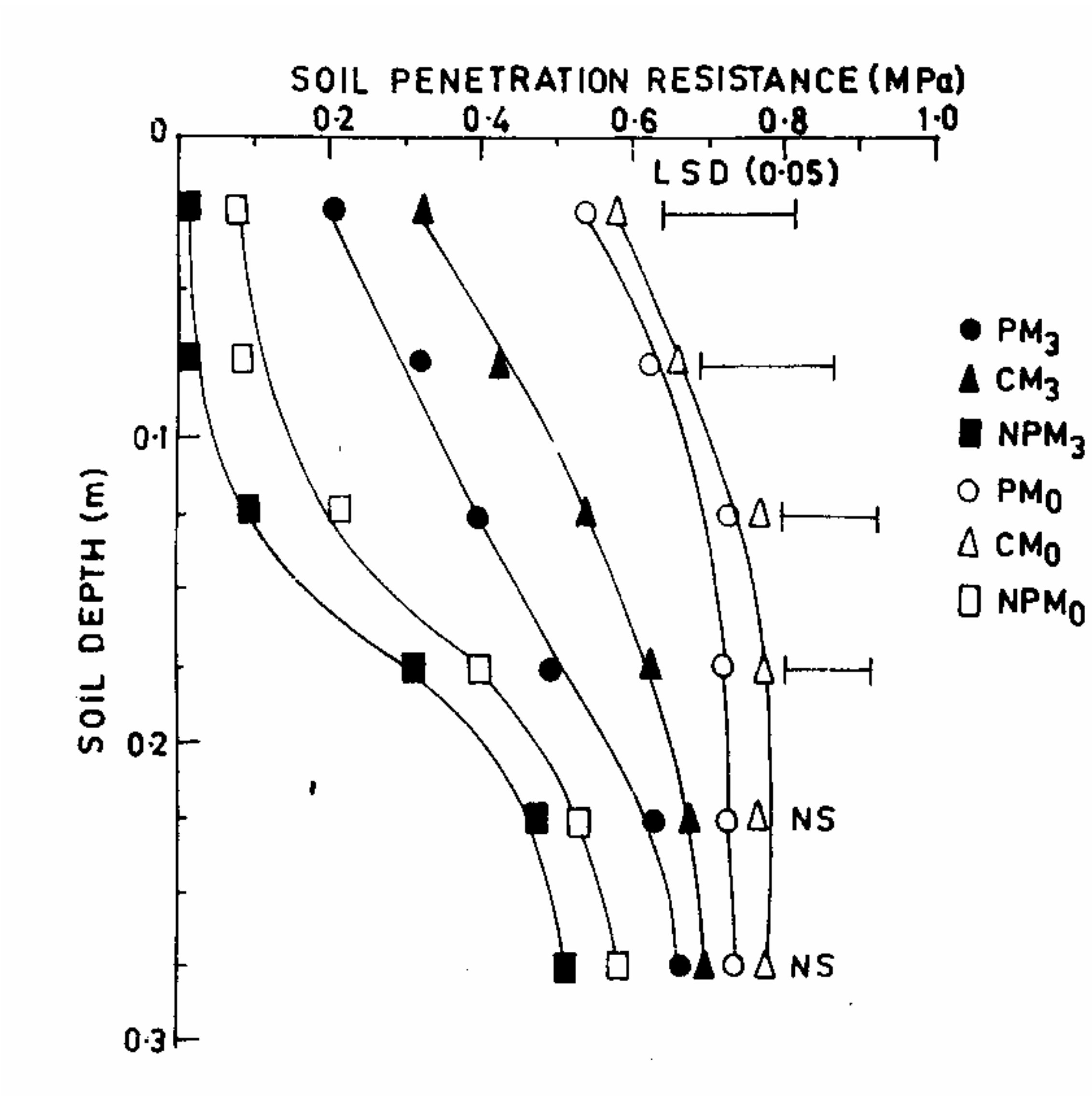

Fig.1 Soil penetration resistance one month after rice harvest for the 0-0.30 m depth under various treatments. . P= Puddled; NP= Non puddle;C= Compaction; M0= No residue; M3= 30 tha^{-1}residue addition. (Bhagat et al., 1994)

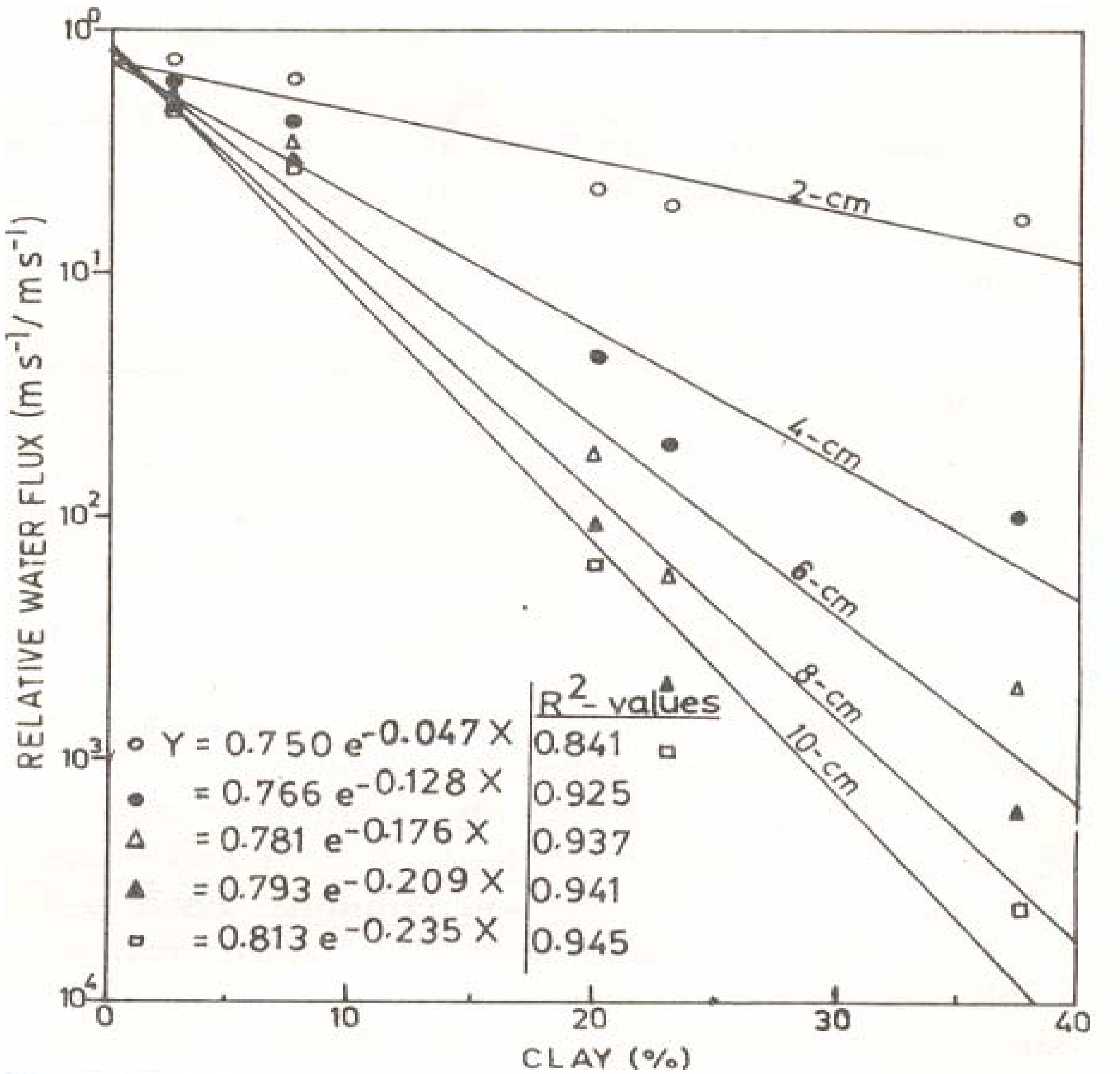

Fig 2. Relative water flux (the ratio of water flux in puddle to the one in non puddle soil) in relation to the clay content of soils. (Sharma and Bhagat, 1993)

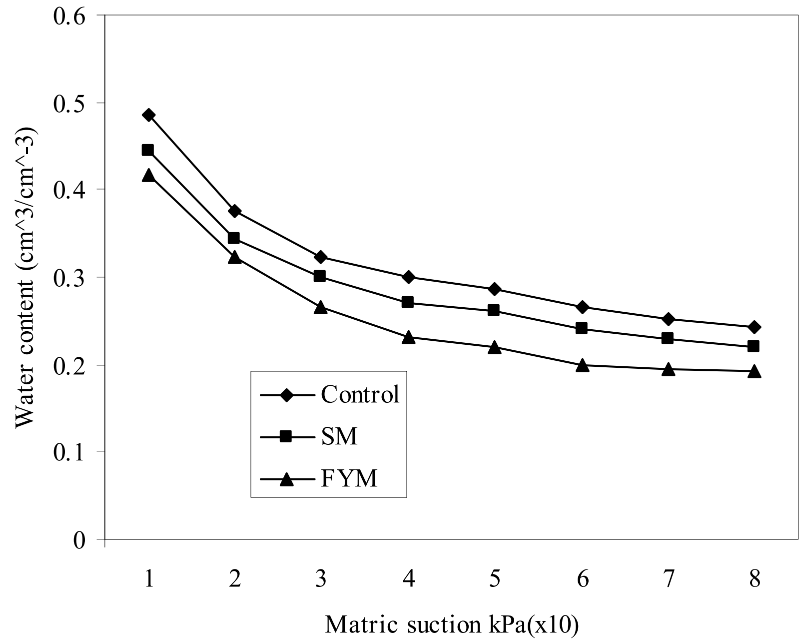

Fig. 3. Soil water release curves under different treatments. Control=Puddling with no residue; SM= Straw mulching; Farm yard Manure. (Bhagat and Verma, 1991)