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A Three-stage Soil Layer Mixing Plough for the Improvement of Meadow Soil, Part 1: Mechanical Properties of Soils

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Meadow soil in China consists of extremely fine soil particles, is quite impermeable and has particular mechanical properties. This paper deals with the mechanical properties of the three horizons (Ap, A and Cg1) of meadow soil as an aid to understanding the draught requirement of a three-stage soil layer mixing plough for the improvement of the meadow soil. Pseudogley soil which is a typical heavy clay soil in Japan was also tested for comparison. Tensile strength, shear strength, soil–metal friction and soil–plastic friction were determined.

The results show that the tensile strength of the meadow soil increased steeply at lower soil water contents. In the range of soil water content of more than 30% d.b., the tensile strength of the A horizon is the largest, followed by the Cg1 horizon, Ap horizon and pseudogley soil.

The cohesive strengths of all soils showed a maximum at particular soil water contents. These soil water contents were nearly same as the plastic limits. Comparing the maximum value of the cohesion, the A horizon was the largest, followed by the Cg1, Ap horizon and the pseudogley soil.

The adhesion to steel of all soils showed a maximum at particular soil water contents. These soil water contents were slightly larger than the plastic limits. Hence, the adhesion was highest under a wet soil condition. The maximum value for the adhesion of the A horizon was the largest, followed by the Ap, Cg1 and the pseudogley soil. Hence, all horizons of the meadow soil were much stickier than the pseudogley soil.

The adhesion to polyethylene was smaller than that to steel. The soil water content, at which the adhesion showed a maximum, was the same as that for steel.

1. Introduction

Meadow soil producing poor crop yields is widely distributed on the Three-river plain in the Black Dragon province of the People's Republic of China near the border with Russia which is one of most important grain growing areas in the world.

Figure 1 shows a typical meadow soil for a cultivated field in Baoqing county. The first horizon (Ap) is a humic, black and brown soil which contains abundant organic matter and has an aggregate structure, great pore spaces and good permeability, is suitable for plant growth and has a thickness of about 200 mm. The second horizon (A) is also a humic soil and is black, but the availability of the organic matter is less. Hence, the N percentage is low because of high impermeability due to very heavy clay, and it has a thickness of about 300 mm. The third horizon (Cg1) is the gleyed parent material with a thickness of about 400 mm. It has little organic matter but has a large amount of Fe_2O_3 and hence, it is yellow. The permeability of this horizon is also low because of heavy clay. The fourth horizon (Cg2) below about 900 mm is also gleyed soil, and hence, it is grey and yellow and is also quite impermeable.

With many impermeable horizons due to heavy clay which consist of extremely fine soil particles, the ground water and soil surface water are quite isolated. All the precipitation is held only in the Ap horizon. Plants sometimes suffer due to excess moisture. The improvement of the meadow soil could be achieved by breaking down the

Notation

a_m	adhesion of soil–steel, Pa
a_p	adhesion of soil–polyethylene, Pa
c_0	cohesion of compacted soil, Pa
c_1	cohesion of loosened soil, Pa
d_s	diameter of soil specimen, m
l	length of soil specimen, m
N	normal (perpendicular) load, N
r_1	outer diameter of ring (= 0·05 m)
r_2	inner diameter of ring (= 0·03 m)
T	torque measured, N m
δ_m	angle of soil–steel friction, deg
δ_p	angle of soil–polyethylene friction, deg
θ	soil water content, % d.b.
μ_m	coefficient of wheat straw or maize stalk–steel friction
μ_p	coefficient of wheat straw or maize stalk–polyethylene friction
σ	normal (perpendicular) stress, Pa
σ_t	tensile strength of soil, Pa
τ	shear stress, Pa
φ_0	angle of soil-internal friction of compacted soil, deg
φ_1	angle of soil-internal friction of loosened soil, deg

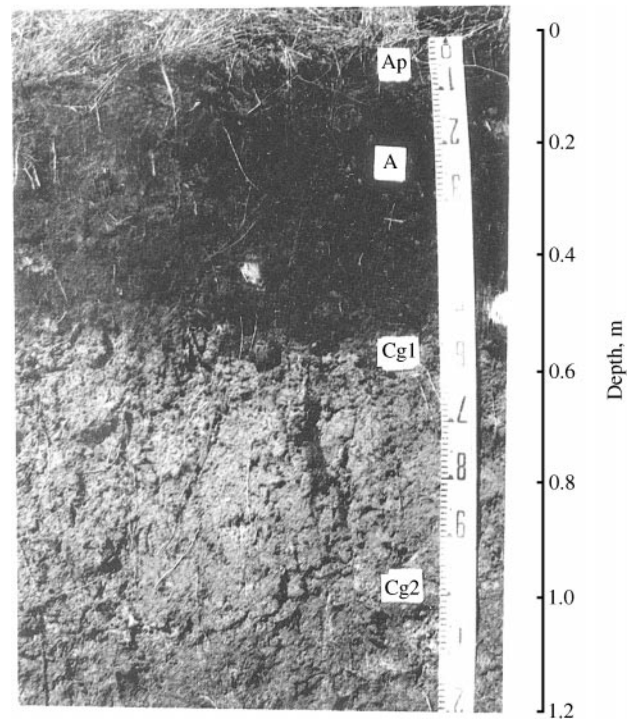

Fig. 1. Typical meadow soil in Baoqing county, People's Republic of China: Ap horizon, humic soil with abundant organic matter and good structure; A horizon, impermeable soil with less organic matter; Cg1 horizon, impermeable gleyed parent material with ferrous oxide; and Cg2 horizon, impermeable gleyed soil

A horizon, the most impermeable horizon which has a thickness of 300 mm and by increasing its permeability. With this treatment, the limited annual precipitation (500–600 mm) could be held in the A horizon, subsoil. The rainfall is uneven here; 60–70% of annual precipitation occurs in July and August, in summer season and there is almost no rainfall in winter and spring seasons. Hence, the plants often suffer due to excess moisture during growing season in summer and due to drought during the sowing season in spring. Such problem of the meadow soil could be solved with this treatment.

In previous papers (Zhang *et al*., 2000a, 2000b, 2000c), a prototype explosive subsoiler was developed, which injected high-pressure gas. A major part of the soil volume failed to withstand the gas pressure, and longer sustainability was obtained. However, it had three faults: it caused excessive combustion noise when in operation, it was rather complicated and costly for mass production and the soil failure capacity of this machine was not sufficient for the soils with the soil penetration resistance of more than 3 MPa (30° penetrometer cone angle, 16 mm base diameter).

In this paper, another new method was envisaged, a three-stage soil layer mixing plough which consists of three plough bodies as shown in *Fig. 2*. This machine mixes trash on the soil surface of the Ap horizon such as wheat straw and maize stalk in *Fig. 1* into the A horizon of the subsoil. With this treatment, the impermeable A horizon would be broken down with soil disturbance, and the permeability would be improved by mixing of the trash because of greater pore spaces created.

The shapes of the plough bodies in *Fig. 2* are special and estimation of the draught requirements of each plough body is required for their development. This paper deals with the determination of the mechanical properties of the meadow soil as an aid to understanding the draught requirement of the special plough. Pseudogley soil which is a typical heavy clay soil in Japan was also tested for comparison. The friction of wheat straw and maize stalk to metal and plastic was also determined.

2. Experimental details

Soil tensile strength, soil shear strength, soil–metal friction and soil–plastic friction were determined. The tensile strengths of soils are generally small, and a conventional tensile test for steel cannot be used because the

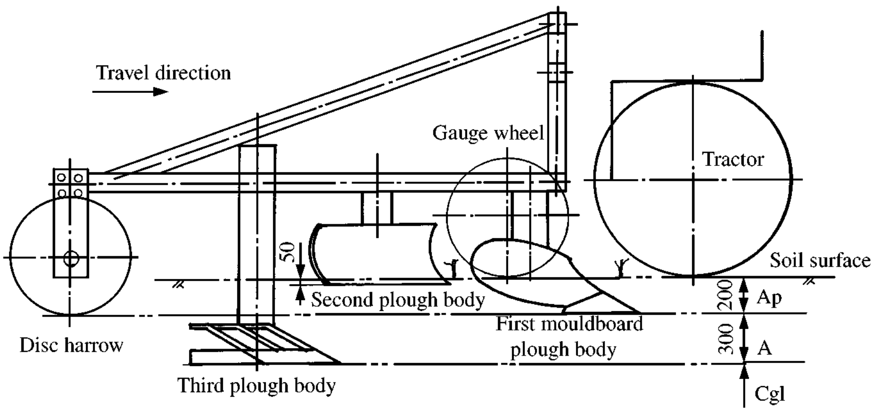

Fig. 2. Schematic diagram of three-stage soil layer mixing plough; Ap, A and Cg1, soil horizons; all dimensions in mm

specimen has to be gripped by a chuck. A radial compression test by Kawamoto (1968) was conducted whereby a cylindrical soil specimen with a diameter d_s of 29 mm and a length l of 15 mm was radially compressed as shown in *Fig. 3*. Kawamoto (1968) reported that with a normal load N distributed over the length of the specimen (line-loading), a tensile stress σ_t is produced transverse to the central line of the specimen of magnitude:

$$\sigma_t = \frac{2N}{\pi d_s l} \tag{1}$$

In the tensile test, the deflection of the specimen in the direction of the load and the amount of load were sensed and recorded on a x–y recorder.

The soil shear and the interface friction tests were conducted with a ring (annular) shear tester (The Japanese Society of Soil Mechanics and Foundation Engineering, 1992). A ring with vanes was used for the soil shear tests and a flat ring for the soil–metal and soil–plastic friction tests. A flat steel ring plated with chromium was used for the soil–metal friction tests, and another flat ring lined with polyethylene was used for the soil–plastic friction tests which would have the least friction resistance to soils. From the measured load and torque, the normal and shear stresses were calculated. The normal stress is given by

$$\sigma = \frac{N}{\pi(r_1^2 - r_2^2)} \tag{2}$$

where σ is the normal stress, r_1 the outer diameter of the ring, r_2 the inner diameter of the ring and N the normal load.

With the torque measured by a torque wrench, the shear stress or the frictional resistance is given by

$$\tau = \frac{3T}{2\pi(r_1^3 - r_2^3)} \tag{3}$$

where τ is the shear stress or frictional resistance and T is the measured torque. Graphs were drawn of τ versus $f(\sigma)$ for each soil and each soil water content. The cohesion c or adhesion a was determined as the value of when $\sigma = 0$, and the angle of internal friction φ or the angle of soil–steel or soil–polyethylene friction δ was determined from the slope of the plot of τ versus $f(\sigma)$.

Three to five runs were made for each condition. The specimens for the shear strength, soil–steel and soil–polyethylene friction tests were all made of the disturbed soils which were taken from the different horizons of the meadow soil and pseudogley soil. The soil water content was adjusted to the required value, and the soil was compacted in a steel mould. The pseudogley soil specimen was compacted to a soil penetration resistance of 0·5 MPa on Yamanaka's hardness tester scale (Japanese Society of Soil Mechanics and Foundation Engineering,

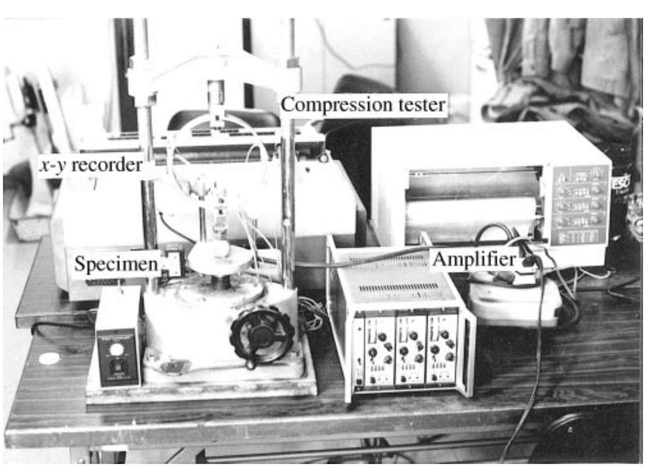

Fig. 3. Radial compression test

Table 1
Mechanical composition of soils in this study

Soil	*Pseudogley*	*Meadow soil horizons*		
		Ap	*A*	*Cg[1]*
Depth, mm	0–600	0–200	200–500	500–900
Coarse sand (2–0·2 mm), %	20·0	1·0	1·0	10·0
Fine sand (0·2–0·02 mm), %	25·0	11·0	7·0	13·0
Silt (0·02–0·002 mm), %	30·0	62·0	33·0	37·0
Clay (< 0·002 mm), %	25·0	26·0	59·0	40·0
Plastic limit, % d.b.	23·7	31·6	35·1	27·4
Liquid limit, % d.b.	34·6	75·2	65·2	52·6
Soil texture	Silty clay	Heavy loam	Heavy clay	Light clay

1992; 25° cone angle, 17 mm base diameter) which was the same as the soil in the soil bin test. For the meadow soil, since 1997, the soil penetration resistance of each horizon of the field has been measured by the Yamanaka hardness tester at different soil water contents and, hence, the values of the Yamanaka hardness tester scale of each horizon of the field at a certain soil water content are known. The meadow soil specimen at a certain soil water content in the laboratory was compacted to give the same as the known value of Yamanaka hardness tester scale of the field soil versus the same water content.

The specimens for the tensile tests were also made of the same disturbed soils. The water contents of the disturbed soils were first adjusted to around the liquid limit, and then the specimens were formed by a plastic mould and dried in air. Hence, all specimens were slightly different from the original state in the field.

Soils in this study were all heavy clay soils: the pseudogley soil in Japan; and Ap, A and Cg1 horizons of the meadow soil in China as shown in Table 1. The texture of the pseudogley soil is silty clay. *Figure 4* shows the accumulated percentage of soil particles of the four soils in Table 1. The soil particles of any horizon of the meadow soil are much finer than that of the pseudogley soil. Especially in the A horizon, 60% of the soil particles is less than 0·002 mm and the A horizon belongs to very heavy clay. Hence, it is essential for the improvement of the meadow soil to increase the permeability of the A horizon.

When the second plough body in *Fig. 2* is developed, the mechanical properties of tilled and loosened soils are required. Hence, shear tests of the loosened soils were also carried out.

3. Results and discussion

3.1. *Tensile strength*

A vertical crack was produced in the specimen by radial compression as shown in *Fig. 5.* The maximum load N was determined, and the tensile strength σ_t was

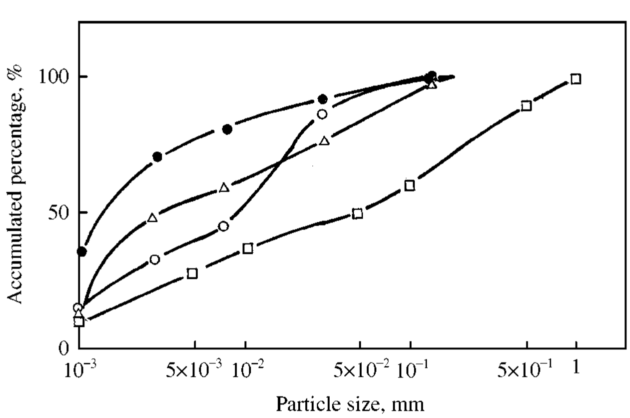

Fig. 4. Particle size accumulation curves of soils in this study: □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

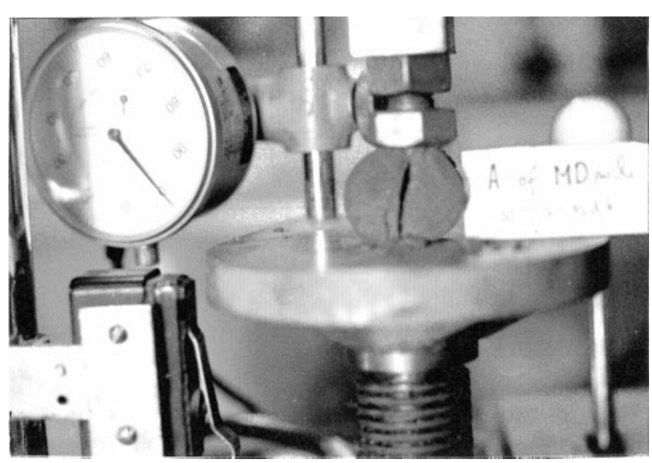

Fig. 5. A vertical crack produced by radial compression of the soil sample

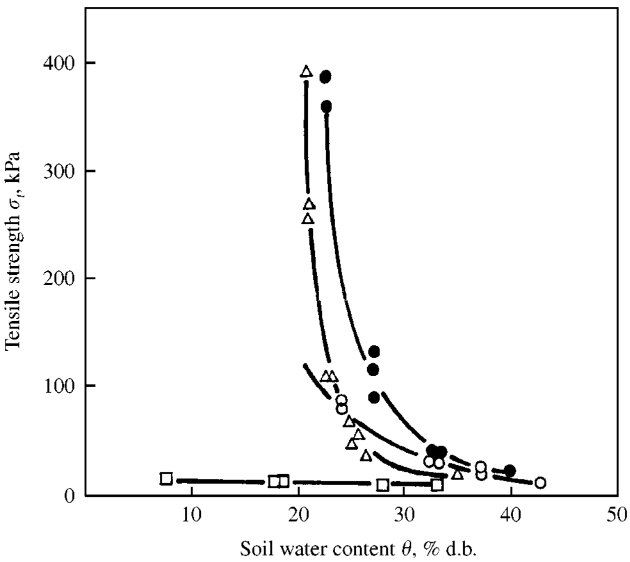

Fig. 6. Tensile strength (σ_t) as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

calculated by Eqn (1). The results are shown in *Fig. 6*. The tensile strength of the pseudogley soil was essentially unaffected by soil water content. The tensile strengths of the meadow soil increased steeply at a lower soil water content. The commonly occurring soil water content in the actual meadow soil fields was more than 30% d.b. In this range, the tensile strength of the A horizon is the largest, followed by the Cg1 horizon, Ap horizon and pseudogley soil.

Comparing the values in *Fig. 6* with those of the planosol which is distributed in the same Three-river plain in the Black Dragon province (Jia *et al*., 1998), the trends of all three horizons of the meadow soil are the same as that of the Aw horizon of the planosol, namely, the tensile strength increased steeply at around 20% d.b. in the soil water content. This would be a characteristic of heavy clay soils.

3.2. *Cohesion*

The cohesion of each soil in *Fig. 7* showed a maximum at a particular soil water content which was nearly the same as the appropriate plastic limit in Table 1. Comparing the maximum values c_0, that for the A horizon was the largest, followed by those for the Cg1, Ap horizon and the pseudogley soil.

Comparing the values in *Fig. 7* to the tensile strength σ_t in *Fig*. 6 at soil water contents of more than 30% d.b., the value of σ_t for the pseudogley soil is about one-seventh of the value of c_0 but the values of σ_t for all meadow soils are nearly the same as c_0.

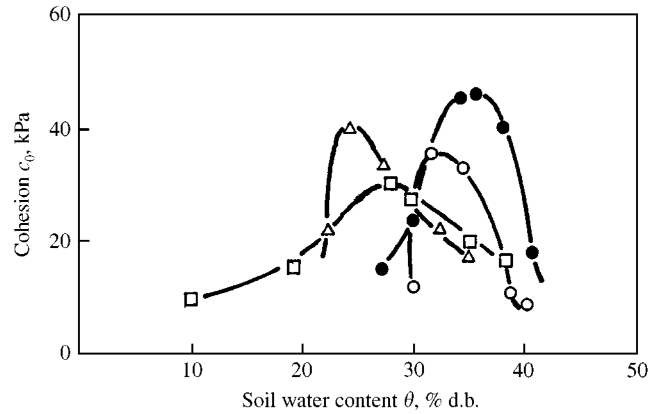

Fig. 7. Cohesion (c_0) of compacted soils as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

Comparing the cohesion values in *Fig. 7* with those of the planosol (Jia *et al*., 1998), the cohesion of all horizons of the planosol are larger than those of the meadow soil; especially the maximum cohesion of the second horizon (Aw) of the planosol which was 60 kPa. Hence, the planosol is an extremely strong soil.

The cohesion of the loosened and soft soils c_1 are shown in *Fig. 8*. The cohesion values in *Fig. 8* were smaller than those in *Fig*. 7. The particular soil water contents in *Fig. 8* at which a maximum cohesion is shown were the same as in *Fig. 7*.

3.3. *Adhesion*

The adhesion to steel a_m for the different soil type is shown in *Fig. 9*. The adhesion of each soil showed a maximum at particular soil water content. These soil water

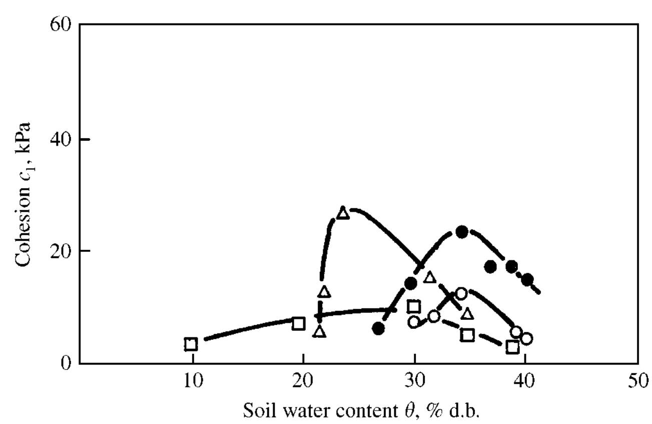

Fig. 8. Cohesion (c_1) of loosened soils as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

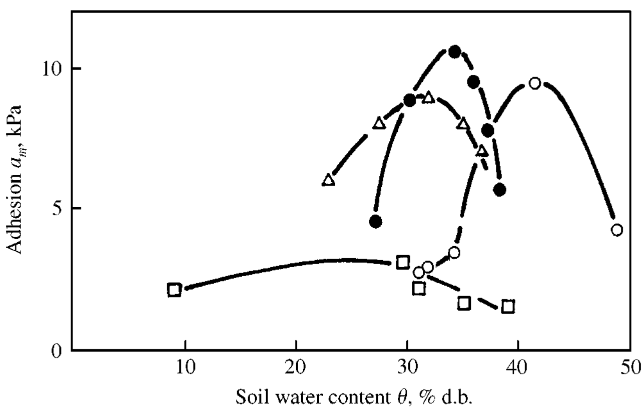

Fig. 9. Adhesion (a_m) of soil–steel friction as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

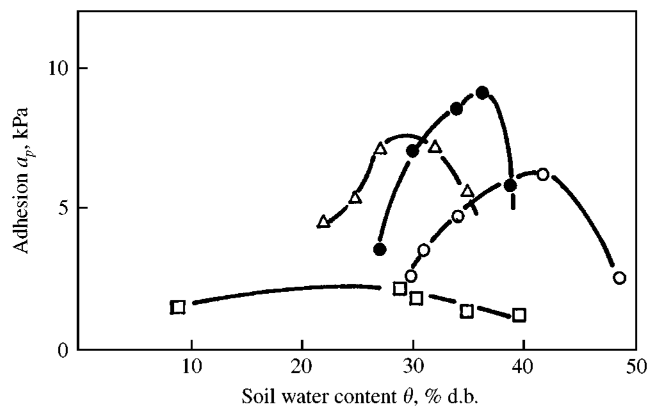

Fig. 10. Adhesion (a_p) of soil–polyethylene friction as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

contents were slightly higher than those for the plastic limits in *Figs 7* and *8*. Hence, the adhesion reached a maximum under wetter soil conditions. The maximum value of the adhesion of the A horizon was the largest, followed by the Ap, Cg1 and the pseudogley soil. Hence, all horizons of the meadow soil were much sticky than the pseudogley soil.

Comparing the values in *Fig. 9* with the values of the cohesion in *Fig. 8*, there is a zone where the adhesion to steel was larger than the cohesion of the loosened soil, for instance, the zone where the soil water content of the Ap horizon is 30–40% d.b. Here, the soil does not peel from steel but accumulates on it as reported by Ai (1973).

Comparing the values in *Fig. 9* with those of the planosol (Jia *et al.*, 1998), the values for the adhesion of the first and second (Ap and A) horizons of the meadow soil are larger than those for the first and second horizons of the planosol, and hence, the Ap and A horizons of the meadow soil adhere more easily to steel. The adhesion of the third horizon (Cg1) of the meadow soil is smaller than that of the third horizon (B) of the planosol. This is because the B horizon of the planosol is also heavy clay.

The soil adhesion to polyethylene a_p is shown in *Fig. 10*. These values were smaller than those for a_m on steel in *Fig. 9*. The soil water contents, at which the adhesion showed a maximum, was the same as those in *Fig. 9*.

3.4. *Angle of internal friction*

From the lines of τ *versus* $f(\sigma)$ of the compacted soils, the slopes of the lines φ_0, which denote the angle of internal friction were determined and are shown in *Fig. 11*. The angles of internal friction of all soils decreased as soil water content increased, and hence, the shear strength is less dependent on the normal stress at higher soil water contents. The angles of internal friction of all soils became constant when the soil water contents were greater than the liquid limits. At commonly occurring soil water content in the fields, around 30% d.b., the angles of internal friction of the Ap and A horizons were great and hence, if there is a normal stress σ, these soil would show a great shear resistance.

Figure 12 shows the angles of internal friction of the loosened soils φ_1. The trends of the loosened soils for soil water content were the same as those of the compacted soils in *Fig. 11*. The values of φ_1 were nearly same as the values of φ_0.

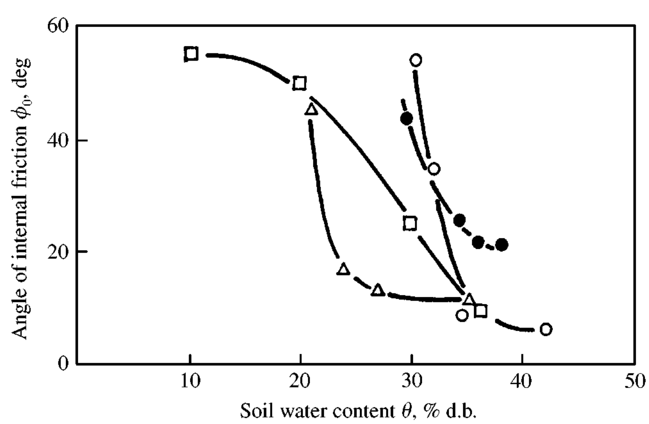

Fig. 11. Angle of internal friction of compacted soils (ϕ_0) as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

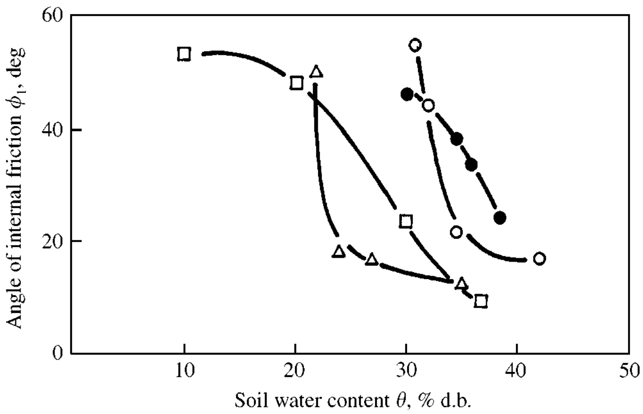

Fig. 12. Angle of internal friction of loosened soils (ϕ_l) as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

3.5. *Soil interface friction*

Figure 13 shows the angle of soil–steel friction δ_m. The values of δ_m were 10–25° and less than the values of 10–40° of the planosol (Jia *et al.*, 1998). Hence, the meadow soil adheres more easily than the planosol regardless of the amount of the normal stress.

Figure 14 shows the angle of soil–polyethylene friction δ_p. The trend in *Fig. 14* was the same as that of soil–steel friction in *Fig. 13*. The values of δ_p were slightly smaller than those of δ_m and were 5–20°.

3.6. *Interface friction of wheat straw and maize stalks*

Table 2 shows the friction test results for wheat straw and maize stalks. The wheat straw and maize stalks were dry and their water content were 12–13% d.b. The adhesion a_m of wheat straw to steel was 2·0 kPa and that of maize stalk to steel was 1·5 kPa. These values are 1/5–1/10 of soil–steel friction. The angles of friction of both materials δ_m were 17–18°and were nearly the same as the values of soil–steel friction in *Fig. 13*.

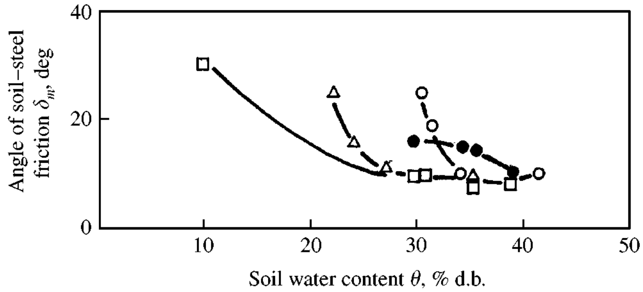

Fig. 13. Angle of soil–steel friction (δ_m) as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

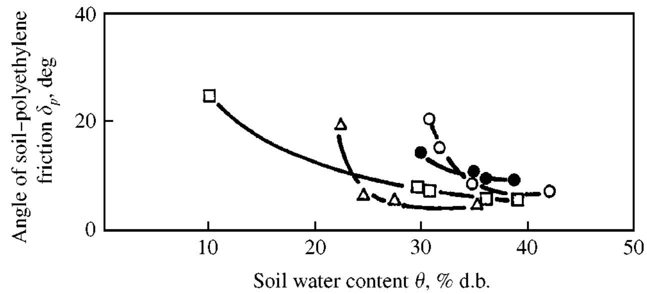

Fig. 14. Angle of soil–polyethylene friction (δ_p) as a function of soil water content (θ): □, pseudogley soil; ○, meadow soil horizon Ap; ●, meadow soil horizon A; △, meadow soil horizon Cg1

The adhesion a_p of wheat straw to polyethylene was 1·5 kPa which is slightly smaller than that of soil–polyethylene, but the value for maize stalk to polyethylene adhesion was the same as that of the soil–polyethylene. The angles of interface friction for wheat straw and maize stalk were much smaller for polyethylene δ_p than for steel δ_m. Especially, the angle of friction between maize stalk and polyethylene was only 7°, and was almost unaffected by increasing normal stress σ. The values of μ_m and μ_p in Table 2 are coefficient of friction of wheat straw and maize stalk to steel and polyethylene, respectively, and the tangent values of the friction angles δ.

4. Conclusions

(1) The tensile strength of the meadow soil increased steeply at lower soil water content. The commonly occurring soil water content in the actual meadow soil fields was more than 30% d.b. In this range, the tensile strength of the A horizon is the largest, followed by the Cg1 horizon, Ap horizon and pseudogley soil.
(2) The cohesion of each soil showed a maximum at a particular soil water content which was nearly the same as that for the appropriate plastic limit. Comparing the maximum values of the cohesion, that for the A horizon was the largest, followed by those for the Cg1 horizon, the Ap horizon and the pseudogley soil.
(3) The adhesion to steel of each soil showed a maximum at a particular soil water content which was slightly larger than that for the appropriate plastic limit. Hence, the adhesion reached a maximum under

Table 2
Friction of wheat straw and maize stalk

	Water content % d.b.	*Metal*			*Polyethylene*		
		Adhesion a_m, kPa	*Friction angle δ_m, deg*	*Coeff. of friction μ_m*	*Adhesion a_p, kPa*	*Friction angle δ_p, deg*	*Coeff. of friction μ_p*
Wheat straw	12·1	2·0	17·0	0·31	1·5	10·0	0·18
Maize stalk	13·5	1·5	18·0	0·32	1·5	7·0	0·12

wetter soil conditions. The maximum value of the adhesion of the A horizon was the largest, followed by those for the Ap horizon, the Cg1 horizon, and the pseudogley soil. Hence, all horizons of the meadow soil were much stickier than the pseudogley soil.

(4) The adhesion to polyethylene was less than that to steel. The soil water content, at which the adhesion showed a maximum for polyethylene, was the same as that for steel.

(5) The angles of internal friction of all soils decreased as soil water content increased, and hence, the shear strength is less dependent on normal stress at higher soil water contents. The angles of internal friction of all soils became constant when the soil water contents were greater than the liquid limits.

(6) The angle of soil–steel friction for meadow soil was 10–25° and was less than the values of 10–40° for the planosol. Hence, the meadow soil adheres more easily than the planosol regardless of the amount of the normal stress.

(7) The trend of the angle of soil–polyethylene friction was the same as that of soil–steel friction. The values of the angle of soil–polyethylene friction were slightly smaller than those of soil–steel and were 5–20°.

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