SOIL FRIABILITY

W. H. UTOMO and A. R. DEXTER

(*Waite Agricultural Research Institute, Glen Osmond, South Australia 5064*)

Summary

Soil friability is defined and a method for its measurement is developed from the theory of brittle fracture of soil aggregates. The variation in friability with soil water content is in good agreement with the results of tillage experiments done by earlier workers. It is found that Urrbrae and Strathalbyn sandy loams are most friable at water contents approximately equal to their Casagrande Plastic Limits.

The method is applied to study the effects of wetting and drying cycles, freezing and thawing cycles, and phosphoric acid treatment on the friability of the Urrbrae soil. It is found that all of these treatments increase soil friability as defined.

Introduction

THE APPLICATION of conventional soil mechanics to tillage (*e.g.* Payne, 1956) predicts that the sizes of the primary fragments sheared from the bulk (undisturbed) soil are independent of the shear cohesion and only slightly affected by the angle of internal friction. Whilst these types of theory are useful for predicting the draught forces of simple implements, they are of no use in predicting the amount of soil fragmentation produced by tillage. Even casual observation shows that different soils, or even the same soil at different water contents, fragment quite differently. Clearly, a factor other than the conventional soil mechanical quantities must be implicated, and in this paper we define and investigate the significance of a measure of soil friability on soil fragmentation under mechanical stress.

The term 'soil friability' has been defined as the tendency of a mass of unconfined soil in bulk to crumble and break down under applied stress into smaller fragments, aggregates and individual soil particles (Bodman, 1949). Christensen (1930) employed stress-strain relationships in an attempt to measure soil friability, and Jamison (1954) used the modulus of rupture test. Both of these approaches, however, only measure how easily the soil is worked, that is, soil strength: neither took account of the size distribution of the resulting pulverized fragments.

One of the aims of tillage is to break up the large soil mass into smaller clods or aggregates. It is therefore desirable that the material of the smaller fragments, which originally comprised the larger clods, has a relatively greater strength than that of the larger clods, otherwise, the soil mass could break down into individual mineral particles or dust. With this aim in mind, we have modified and sharpened Bodman's definition of soil friability to 'the tendency of a mass of unconfined soil to breakdown and crumble under applied stress into a particular size range of smaller fragments'.

Braunack *et al.* (1979) found that the tensile strength of soil aggregates

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is a function of aggregate size: the larger the aggregates, the smaller the mean tensile strength. If the logarithm of aggregate volume V, is taken as the abscissa, and the logarithm of tensile strength, S, is taken as the ordinate, then the relationship is a straight line

$$\log_e S = -k \log_e V + A \quad (1)$$

where

$$A = \log_e[S_o V_o^k \Gamma(1 + k)] \quad (2)$$

Here, S_o and V_o are the strength and volume respectively of the basic soil elements which comprise the bulk aggregates, Γ is the tabulated Gamma function, and k is an adjustable parameter. The parameter k is a measure of the dispersion of the strengths of the micro-cracks and flaws within the clods or aggregates. The intercept A is, in effect, an extrapolated estimate of the tensile strength of 1 m^3 samples of the bulk soil.

A comparison of the objective of tillage with the definition of soil friability given above leads to the conclusion that Equation (1) can be used to measure soil friability. The value of k is an indication of how readily large clods will break down into a range of smaller soil aggregates. Large k values indicate that the larger clods have a much smaller strength than the smaller clods or aggregates and may thus be more readily fragmented into smaller stronger units. Very small k values, on the other hand, indicate that the strength of the large clods does not differ much from that of any smaller fragments. In these cases, when a mass of soil is stressed by tillage, it will break into aggregates and clods or arbitrary size.

In the following, we identify the parameter k of Equation (1) with soil friability and discuss it as a quantity separate from soil strength. Thus a soil of any strength can have any value of friability, k.

Materials and methods

Soils

Experiments were done with Urrbrae fine sandy loam from the Waite Agricultural Research Institute (34° 58′ S, 138° 38′ E) and on Strathalbyn sandy loam from the Charlick Experiment Station 50 km further south. Urrbrae loam is a red brown earth, and the Strathalbyn loam is a shallower red brown earth typical of a lower rainfall area. Some physical properties of these soils are given in Table 1.

TABLE 1
Composition and Atterberg limits of the soils

Soil	*Proportion of oven dry soil (%)* *<20 μm*	 *<2 μm*	*Organic matter (%)*	*Plastic limit (%)*	*Liquid limit (%)*
Urrbrae	49	17	1.7	19.5	26.5
Strathalbyn	36	12	2.8	17.9	30.5

Soil water content

Soil water content at the time of tillage influences the size distribution of the resulting clods (Lyles and Woodruff, 1962; Bhushan and Ghildyal, 1972; Ojeniyi and Dexter, 1979). Since there is an optimum soil water content for tillage at which the maximum fragmentation is produced, it was decided to test whether a maximum in friability, as measured by k in Equation (1), also occurred at a similar water content.

Aggregates with diameters of 2.0–4.0, 4.0–6.7, 6.7–9.5 and 9.5–17 mm were collected by dry sieving from the *A* horizons of these soils. These aggregates were air dried, slowly wetted close to saturation by capillary action, and then dried to −10, −50, −100 and −500 kPa water matric potentials. Drying to −10 kPa was done in sintered glass funnels and to the other potentials on pressure plates.

The tensile strengths of 20 aggregates of each diameter class at each water potential for each soil were measured by crushing the aggregates between parallel plates (Rogowski, 1964; Dexter, 1975). The tensile strength was calculated for each aggregate using the equation

$$S = 0.576F/d^2 \quad (3)$$

where F is the polar force required to fracture the aggregate, and d is the aggregate diameter. It is interesting to note that positive (compressive) forces in one direction can give rise to tensile stresses and failure in another.

The failure was tensile even for samples wetter than the plastic limit. For the wetter aggregates, plastic deformation caused slight flattening at the poles (the points of loading). Flattening to the extent where the diameter of the flattened portion equals 0.27 of the distance betwen the flattened portions at failure has been found to have a negligible effect on tensile strength measurements of loaded cylinders in the Brazilian test (Frydman, 1964). It is likely that, with the aggregates used here, where less flattening than this occurred, there was also a negligible effect of plastic deformation.

Wetting and drying

It is known that wetting and drying cycles can reduce the tensile strength or modulus of rupture of soil and that increased amplitudes of wetting and drying can result in greater soil fragmentation on tillage. The latter is the 'tilth mellowing' effect. The following experiment was designed to investigate the effect of wetting and drying cycles on soil friability.

Soil from the *A* horizon of Urrbrae loam was passed through a 1 mm sieve and remoulded at 20 per cent water content with distilled water. This remoulded soil was allowed to equilibrate overnight and was then again remoulded. Aggregates with diameters of about 5, 8, 10, 13 and 17 mm were made by rolling this soil by hand. To eliminate any confounding effects from thixotropic (age) hardening, these aggregates were aged at −100 kPa potential in a pressure plate apparatus for 2 weeks.

The aggregates were then treated as follows

(a) control (kept at −100 kPa potential)
(b) subjected to wetting (−10 kPa) and drying (−100 kPa) cycles.

Wetting and drying cycles were done in sintered glass funnels and pressure plate apparatus respectively.

Tensile strength was measured by crushing 16 aggregates of each size for each treatment between parallel plates as described before.

Freezing and thawing

The idea was the same as with the wetting and drying experiment as discussed above.

The remoulded Urrbrae aggregates were made as described in the wetting and drying experiment. The treatment was

(a) control
(b) subjected to freezing and thawing cycles.

Freezing was at −15 °C for one day, and thawing was at 20 °C for one day. After completing the freezing and thawing cycles, all treatments were dried to −100 kPa potential in a pressure plate apparatus for two days. The tensile strengths of 16 aggregates of each size for each treatment were then measured as described before.

Acid treatment

Soil from the *A* horizon of Urrbrae loam was passed through a 1 mm sieve and remoulded at 35 per cent water content with (a) distilled water (control treatment), (b) 0.1 M H_3PO_4, (c) 0.2 M H_3PO_4, and (d) 0.5 M H_3PO_4 solution. These samples were allowed to rest and air-dry at ambient temperatures for 6 weeks for the reactions to proceed and for any soil aggregation to develop.

Aggregates with diameter ranges of 2.0–4.0, 4.0–6.7, 6.7–9.5 and 9.5–18 mm were separated from these samples by dry sieving. The aggregates were dried over saturated $CaCl_2$ solution at 20 °C in a vacuum desiccator for 3 weeks to produce an effective water matric potential of −153 MPa. The tensile strength of 20 aggregates of each diameter class for each treatment were measured as described previously.

Results and Discussion

The influence of soil water content

The effect of soil water content and aggregate volume on the tensile strength of Urrbrae loam are shown in Fig. 1. The variation of the derived parameters k and A together with the tensile strength of 10 mm diameter aggregates as a reference are given for both soils in Table 2.

At low water contents, aggregates of both the Urrbrae and Strathalbyn soils have a small k value and a large tensile strength, that is, the soils are very difficult to crush. At high water contents the soils have relatively small strengths. However, they are not suitable for tillage because the soil would turn into arbitrary sizes of clods as shown by the small value of k. Maximum values of k = 0.28 for the Urrbrae and k = 0.22 for the Strathalbyn soils were obtained at intermediate water contents corresponding to a water matric potential of −100 kPa. Under these conditions the soil was considered to be friable.

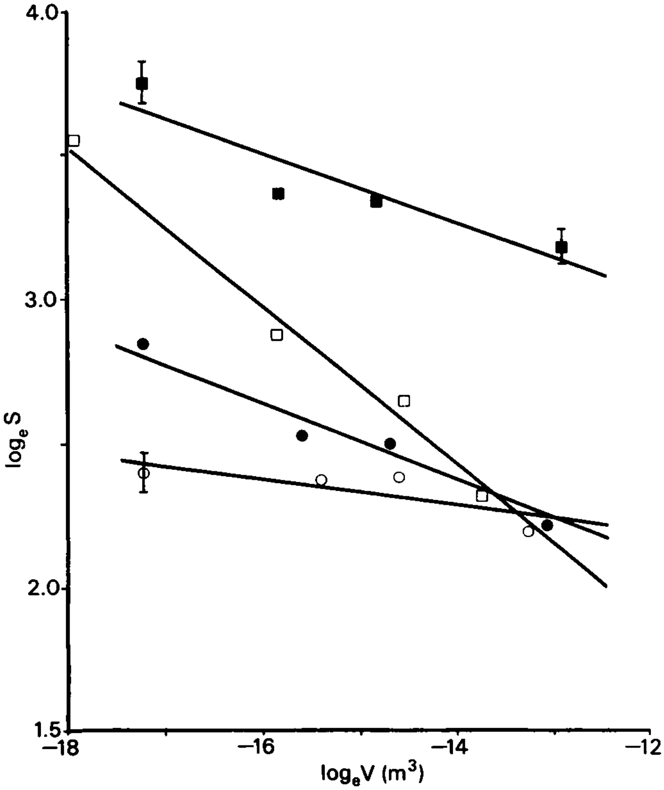

FIG. 1. Effect of soil water content on the tensile strength of natural aggregates of the Urrbrae soil. The continuous curves are fits of Equation (1), and the measurements are given by ○ (−10 kPa); ● (−50 kPa); □ (−100 kPa); and ■ (−500 kPa).

TABLE 2

Effect of water content of Urrbrae loam on the value of k and A parameters of Equation (1) and on the strength S_{10}, of 10 mm diameter aggregates

	Urrbrae				*Strathalbyn*			
Soil water potential (kPa)	*Water content (%)*	*k*	*A (kPa)*	S_{10} *(kPa)*	*Water content (%)*	*k*	*A (kPa)*	S_{10} *(kPa)*
−10	30.2	0.05	1.64	10.1	34.6	0.10	0.54	7.7
−50	22.4	0.13	0.56	11.5	25.6	0.16	0.02	10.0
−100	18.1	0.28	−1.48	12.7	16.3	0.22	−0.55	13.5
−500	12.3	0.12	1.60	27.1	11.8	0.17	0.65	23.3
−153,000*	~2	0.07	3.06	59.1				

*Calculated from the data of Braunack *et al.* (1979)

Some earlier workers found that large clods were produced when tillage was done at very low or very high water contents (Lyles and Woodruff, 1962; Bhushan and Ghildyal, 1972). For the Urrbrae loam, Ojeniyi and Dexter (1979) found that the water content giving the maximum soil crumbling on tillage is around 0.9–1.0 of the Casagrande Plastic Limit. This is in good agreement with the observed peak in friability found in this experiment.

The k values in Table 2 can be fitted to quadratic equations as was done in the tillage experiments of Ojeniyi and Dexter (1979). They normalized the soil water contents by dividing them by the Casagrande Plastic Limits (PL). The intention was to make the results as far as possible independent of soil type. The same procedure was adopted here, and differentiation of the resulting equations showed that the maximum value of k occurs at a gravimetric water content close to $w/\mathrm{PL} = 1.0$. This is the same water content at which maximum soil fragmentation was found to occur during tillage as described above. Although these preliminary results indicate that k may be a good measure of how much soil break-up occurs during tillage, more detailed experiments will be needed on a range of soil types to test this hypothesis adequately.

It seems that the influence of aggregate volume on soil strength becomes small at water contents significantly different from the Plastic Limit. It is probably that at high water contents some flaws close so that the strength of the soil is no longer limited by flaw severity. Under these conditions, soil strength mainly originates from the matric potential of the soil water. It must be kept in mind, however, that the closure of flaws caused by swelling (or their filling by water under tension) does not result in a net increase in soil strength. As discussed above, the inter-flaw soil strength becomes weakened directly with increases in soil water content. The reason for the observed decrease in k at small water contents is not yet understood.

Effect of wetting and drying

The tensile strength of untreated remoulded aggregates was little affected by aggregate volume as shown in Fig. 2. This is shown by the small value of k given in Table 3. Thus the flaws in these aggregates are much smaller than the size of the smallest aggregates used and also had a small dispersion of strengths.

As the aggregates are wetted and dried, the distribution of flaw strengths increases (flaw strength is the stress required to propagate a flaw). As a result, wetting and drying not only decreases aggregate tensile strength but also increases the k value. It is thought that the decrease in aggregate strength with wetting and drying is a result of the formation of micro-cracks caused by unequal swelling and shrinking.

It can be seen in Table 3 that the maximum k value was attained after only one wetting and drying cycle. Additional wetting and drying cycles resulted in a slight decrease in k. Results for natural field aggregates are also included in Table 3 and are here assumed to be in the ultimate equilibrium state having been through an infinite number of natural wetting and drying cycles. This is a first approximation because it is possible that previous soil management can affect this equilibrium value.

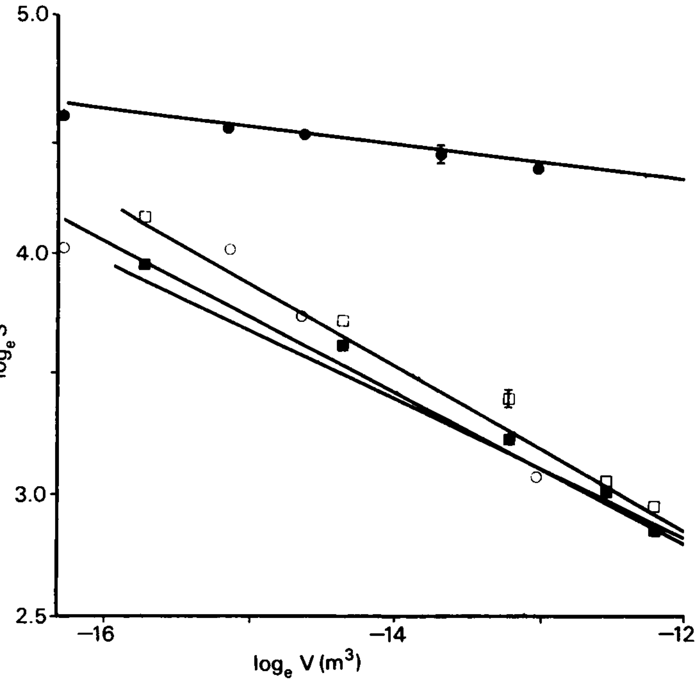

FIG. 2. Effect of wetting and drying on soil tensile strength, S. The continuous curves are fits of Equation (1). The measurements are given by ● (control); ○, □ (1 cycle)(duplicate experiments); and ■ (3 cycles.

From the data in Table 3, it is not possible to fit an equation to the variation of k with wetting and drying. Before this can be done, it will be necessary to experiment with different (smaller) amounts of wetting and drying between different soil water potentials. However, it is possible to obtain very crude equations to estimate the decrease of the tensile strength, S of aggregates of diameter d with the number of wetting and drying cycles, n:

$$S_d = a + b \exp(-cn), \tag{4}$$

where a, b and c are adjustable parameters. We have set the parameter a

TABLE 3

Effect of wetting and drying cycles on the value of k and A parameters of Equation (1) and on the tensile strengths, S_d, of aggregates of diameter d (mm)

Wetting and drying cycles	*k*	*A* (*kPa*)	S_5 (*kPa*)	S_{10} (*kPa*)	S_{20} (*kPa*)
Control (none)	0.07	3.48	103.3	89.33	77.23
1 cycle	0.33	−1.15	74.4	37.44	18.85
3 cycles	0.29	−0.67	62.0	33.92	18.6
∞ cycles (field aggregates)	0.28	−1.48	23.4	13.06	7.30

in each case to be equal to the value of S after ∞ cycles. This procedure gives values of c equal to 0.23, 0.38 and 0.52 for aggregates of 5, 10 and 20 mm diameter respectively. Alternatively, S_d can be expressed in terms of the sum of water content changes (Δw) since remoulding, by

$$S_d = a + b \exp(-C\Sigma\Delta w) \tag{5}$$

This gives values of C equal to 0.0095, 0.015 and 0.022 for 5, 10 and 20 mm diameter aggregates respectively. Equation (5) would be more useful for considering the effects of successive wetting and drying cycles of different amplitude such as occur naturally (see Utomo and Dexter, 1981). These trends in c and C illustrate the fact that larger aggregates get weaker more rapidly than smaller aggregates with wetting and drying. This is probably a consequence of the fact that uneven (from one side only) wetting and drying can cause greater internal stresses (and hence internal flaws) in larger aggregates than in smaller aggregates.

Effect of freezing and thawing

The effects of freezing and thawing on the parameters k and A of Equation (1), together with the strength of 10 mm aggregates are given in Table 4. As in the wetting and drying process, freezing and thawing also decreases aggregate tensile strength and increases k.

The weakening due to freezing and thawing cycles is also due to micro-crack formation. The mechanism of crack formation, however, is of course not the same as that in the wetting and drying cycles. In this case, the cracks are formed as a result of ice formation. Thus the 9 per cent increase in the volume of water in soil when it is frozen disrupts soil bonds, and results in crack formation. In certain soils under certain conditions ice lenses can be formed. These cracks, especially the outer cracks in the aggregates, were visible to the naked eye. The cracks produced by wetting and drying were not so apparent.

Effects of acid treatment

It was found that the application of phosphoric acid to the Urrbrae soil reduced aggregate tensile strength and increased the value of k (Table 5).

The decrease in the strength of remoulded soil due to phosphoric acid treatment has been observed by Lutz and Pinto (1965) and Yeoh (1979).

TABLE 4

Effect of freezing and thawing cycles on the value of k and A parameters of Equation (1) and on the tensile strengths, S_{10}, of 10 mm diameter aggregates

Freezing and thawing	*k*	*A* (*kPa*)	S_{10} (*kPa*)
Control	0.04	2.33	18.1
1 cycle	0.10	1.35	15.3
3 cycles	0.08	1.46	14.0

TABLE 5

Effect of phosphoric acid treatment on the value of k and A parameters of Equation (1) and on the strengths, S_{10}, of 10 mm diameter aggregates

Treatment	*k*	*A* (*kPa*)	S_{10} (*kPa*)
Control	0.08	2.42	35.9
0.1 M H_3PO_4	0.10	0.63	18.9
0.2 M H_3PO_4	0.18	0.27	17.6
0.5 M H_3PO_4	0.12	0.86	13.5

Ingles (1970) observed a decrease in unconfined compressive strength, which is a measure of soil cohesion, of soil which had been treated with phosphoric acid 90 days earlier. He suggested that phosphoric acid was incapable of forming insoluble salts, so that it does not increase soil strength, and may even decrease soil strength. The more acceptable explanation is probably that of Yeoh (1979) who observed an increase in the proportion of sand and silt size particles due to phosphoric acid treatment. These larger particles are microaggregates. He suggested that acid treatment decreases the area of contact between soil particles, and hence results in a decrease in attractive forces. This suggestion seems to be correct because it has been found in another study that phosphoric acid increases the resistance of the soil to probe penetration (Utomo, unpublished). Since cohesion decreases with acid treatment, the increase in the resistance to probe penetration might arise from an increase in friction angle caused by the formation of silt and sand size particles.

The larger *k* values which indicate that the tensile strength decreases with aggregate volume supports the above suggestion. The increase in micro-aggregation as evidenced by the increase in silt size and sand size particles would increase the density of internal flaws between them. This, together with the decrease in cementing material, that is clay size particles, would result in a lower bulk strength.

Conclusions

Wetting and drying cycles and freezing and thawing cycles result in internal micro-crack formation which reduces aggregate tensile strength. Since the formation of cracks in large aggregates occurs more intensively than in small aggregates the decrease in strength in the large aggregate occurs more rapidly than that in the smaller aggregates. This results in the increase in the value of *k* which is used as a measure of soil friability. Likewise, phosphoric acid treatment increases soil friability as shown by the decrease in aggregate tensile strength and an increase in the value of *k*. It is difficult to select the magnitude of *k* which must be possessed by a soil for it to be called friable. In spite of this, on the basis of our practical experience of the method we are able to propose the following rather arbitrary classification:

$k < 0.05$ not friable
$k = 0.05–0.10$ slightly friable

$k = 0.10–0.25$ friable
$k = 0.25–0.40$ very friable
$k > 0.40$ mechanically unstable.

These values may be compared with the value of $k = 0$ which applies for the classical, ideal plastic materials.

We have described $k > 0.4$ as being mechanically unstable to be consistent with the observation that large aggregates (> 5 mm) do not occur in virgin self-mulching black earths such as the Waco soil (Coughlan *et al.* 1973) which have the largest k values we have encountered so far (Braunack *et al.*, 1979).

It is important to realize that particular values of friability only apply over particular ranges of aggregate size. This is illustrated by the fact that aggregates larger than 5 mm in the Waco soil (thought to be formed by the compacting effects of machinery) fall on completely different strength-volume curves than the smaller aggregates formed by natural processes (see Fig. 2 in Braunack *et al.*, 1979). Likewise, the extrapolated tensile strengths of 1 m^3 samples, given by the antilogarithm of A in Tables 2 and 3 seem to be excessively small. It is likely that the strength-volume relationship changes for larger clods. Such a change would probably manifest itself as a change in tensile strength at a certain size (as with the Waco soil) or as a sudden change in the slope of the log(strength)-log(volume) curve.

Similar discontinuities must occur with decreasing aggregate size. It is not meaningful for the tensile strength to approach infinity for very small aggregates. A discontinuity would be expected in many soil types at aggregate sizes around the 100–250 μm, which is probably the size of the basic structural elements of the larger aggregates for many soils.

Thus discontinuities in the log (strength)-log (volume) curves, or their differentials, may be indicative of changes in the internal micro-structure and particle bonding mechanisms at that particular size.

The measure of friability, k, described in this paper may prove useful in future studies because friability is almost synonymous with the quality of the physical condition of an unsaturated soil.

Acknowledgements

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