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EFFECT OF AGEING ON COMPRESSION RESISTANCE AND WATER STABILITY OF SOIL AGGREGATES DISTURBED BY TILLAGE

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ABSTRACT

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Two soils of the red brown earth group were tilled in winter with a spring tine cultivator. Samples of the aggregates disturbed by the tillage were collected and stored at constant water content for various periods of time. Sub-samples were used to determine compression resistance and water stability of the aggregates. It was found that with increasing time since disturbance by tillage, both the resistance to compression and the water stability of the aggregates increased significantly. At a given level of external stress, the increase in the resistance to compression was manifest both through a decrease in the final (equilibrium) packing density, and through an increase in the retardation time of the compression process. As a result of these findings, it is possible to recommend that tillage of these and any other soils exhibiting appreciable thixotropic behaviour should be carried out several days before any further compacting vehicular traffic is anticipated on the soil and, preferably, also several days before any anticipated heavy rainstorms.

INTRODUCTION

Since the studies of Scott Blair (1937) and Scott Blair and Cashen (1938), a number of experiments have been done to study the compaction of aggregated agricultural soils. These include McMurdie and Day (1958), Kuipers (1959), Davis et al. (1973), Dexter and Tanner (1974), Dexter (1975), and Braunack and Dexter (1978). A comprehensive reference work (mainly on non-aggregated soils) has been published by the American Society of Agricultural Engineers (1971). An adequate understanding of compaction, however, is still far from being achieved. The compaction problem, meanwhile, is becoming potentially more complex and serious as a consequence of the increasing use of heavier and larger machinery in modern agriculture, often under unsuitable conditions.

Cooper (1971) suggested that care must be taken not to run over tilled soil with heavy loads, because soil that has been broken up and then recompacted is often more dense than it was before tillage. However, he did not give a reason for this phenomenon. One possible explanation comes from the work of Dexter and Tanner (1974) who described the time dependence of the compressibility by the formula

$$D_t = D_f - \Sigma_j D_j \exp(-t/\tau_j) \quad (1)$$

where

$$\Sigma_j D_j = D_f - D_i.$$

Here, D is packing density, or volume proportion of the soil which is occupied by solid mineral particles, and the subscripts t, i and f denote the packing density at time t, the initial and the final packing density, respectively. The retardation time τ_j is a measure of the speed with which the final (equilibrium) packing density is approached when the external pressure is increased instantaneously from an initial value P_i to a final value P_f. They found that a remoulded soil compresses more rapidly than undisturbed soil and therefore suggested that a tilled soil would be more susceptible to compression than a soil which has not been tilled. They also suggested that a retardation time of around 10^3 s might be advantageous for agricultural top soils because it is greater than the loading times imposed by vehicles and implements and yet smaller than the loading times imposed by elongating plant roots. With such a situation, soil compaction by vehicles and implements would be minimized whereas, on the other hand, roots would be able to compress the soil readily and thus elongate with minimal resistance to penetration.

Mitchell (1960) showed that together with the progressive increase in the shear strength of a soil after remoulding, which is known as 'thixotropic hardening' or 'strength regain', there is a corresponding increase in the resistance to compression.

Croney and Coleman (1954) found that shearing a soil resulted in a decrease in soil water potential. When this soil was allowed to rest, there was an increase in soil water potential. This change has been attributed to particle rearrangement within soil aggregates (Mitchell, 1960; Day and Ripple, 1966). Increases in aggregate water stability with ageing have also been found by Blake and Gilman (1970) who studied the change in the water stability of artificial aggregates, and by Arya and Blake (1972) who studied the water stability of aggregates formed by particle coalescence around water drops and by ploughing field soils.

Davis et al. (1973), Dexter (1975) and Braunack and Dexter (1978) related compression of aggregate beds to the tensile strength of the individual aggregates. Braunack and Dexter (1978) showed that the resistance of aggregate beds to compression increases with increasing tensile strength of the individual aggregates according to the empirical equation

$$H/H_i = A + B \exp[a(S/Y) - b(S/Y)^{0.5}]. \quad (2)$$

Here, H is the equilibrium height of the sample at the applied value of uniaxial stress S, H_i is the initial height and Y is the tensile strength of the individual aggregates, respectively. A, B, a, b are adjustable parameters. This equation was applicable up to S/Y = 120.

It has been found that Urrbrae loam, which is an example of the red-brown earth soil group occurring widely in south-eastern Australia, exhibits appreciable thixotropic behaviour. This has been shown by increases in tensile strength and resistance to probe penetration with ageing after remoulding. In another study it has been found that, under the Mediterranean-type climate conditions in South Australia, the daily fluctuation of soil water content is negligible in the 5—10 cm layer of a tilled soil (Ojeniyi and Dexter, 1979a). As a result of these findings, it was hypothesized that simply allowing this soil to rest for a few days after tillage (i.e. without significant drying) would increase aggregate strength and water stability of the tilled soil. These changes should result in a decrease in the susceptibility of the soil to the damaging effects of vehicular compaction and erosion by water.

MATERIALS AND METHODS

Experiments were done with Urrbrae fine sandy loam from the Waite Agricultural Research Institute (lat. 34°58'S; long. 138°38'E) and on Strathalbyn sandy loam from the Charlick Experiment Station 50 km further south. The Urrbrae soil has a clay content of 17%, a plastic limit of 19.5%, a liquid limit of 26.5%, and an organic matter content of 1.7%. The Strathalbyn soil is a shallow red-brown earth typical of a lower rainfall area. It has a clay content of 12%, a plastic limit of 17.9%, a liquid limit of 30%, and an organic matter content of 2.8%.

Tillage of the Urrbrae soil was done with a spring tine cultivator to 10 cm depth in June which is at the beginning of the winter growing season. The soil had not previously been tilled for 1 year. The water content at the time of tillage was 15.5%. The extent to which this tillage formed new aggregates or just disturbed and rearranged existing ones is not known. In the following, these aggregates are described as having been disturbed by tillage.

After tillage, 10 kg of soil was collected from between the tractor wheel tracks, and aggregates of 1.0—2.0 mm diameter were separated from this sample by dry sieving the moist soil. This dry sieving would also have added, by a slight but unknown extent, to the degree of aggregate disturbance. The initial water stability and the initial resistance to compression were measured on sub-samples of these aggregates. The remainder were stored at constant water content for later testing. To do this, aggregates were stored in a beaker, wrapped in thin plastic sheeting and aluminium foil, and stored in a constant temperature room (20°C).

Aggregate water stability was determined by the 'wet sieving' method: 20 g of aggregates were immersed in water for 5 min, then shaken up and down for 5 min. Aggregate stability was calculated as the final proportion of aggregates larger than 0.5 mm diameter. The compression test was done in a standard consolidometer with uniaxial stresses of 0, 2.45, 4.91, 9.81, 14.72, 19.62 and 29.43 kPa. The consolidometer cell was 75 mm in diameter and

14 mm high, and each aggregate bed which was compressed therefore contained about 20,000 aggregates.

RESULTS AND DISCUSSION

Aggregate water stability

It was found that the water stability of aggregates from the Urrbrae loam increased with ageing at constant water content after the disturbance by tillage (Fig. 1). These data were fitted to the exponential equation

$$S_t = S_o + A[1 - \exp(-kt)]\,. \tag{3}$$

Here, S_t is the stability at time t, (in days), S_o is the stability at $t = 0$, and A and k are adjustable parameters. The resulting equation was

$$S_t = 46.6 + 12.1[1 - \exp(-0.19t)]\,. \tag{4}$$

Several processes may be involved in causing an increase in aggregate stability with ageing at constant water content. Organic matter either as a bonding agent or as an energy source for soil microorganism activity may be one of the important factors in increasing this stability. Likewise, the exudates resulting from microorganism activity are likely to be important.

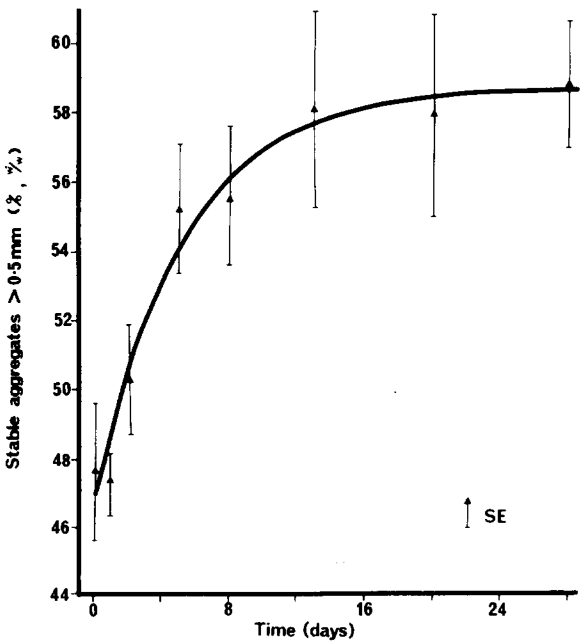

Fig. 1. Effect of ageing since disturbance on the water stability of aggregates of Urrbrae loam. Points are the means of three measurements; the curve is from eq. (4).

Without ignoring the importance of these factors, Blake and Gilman (1970) have suggested that the increase in the water stability of newly-formed aggregates is analogous to the increase in the strength of a remoulded thixotropic soil. It has been shown, that in the absence of organic matter and soil microorganism activity, changes in soil aggregation can still occur (Schweikle et al., 1974).

Here, we suggest that tillage disturbs existing aggregates and probably forms new ones. Mechanical stresses resulting from the passage of the tillage implement rearrange the platy clay particles into a more uniform, parallel arrangement. This increases the repulsive forces between particles resulting from double layer interaction. After tillage, the repulsive forces decrease and the structure tends to adjust to a more random arrangement. Together with this decrease, there will be a corresponding increase in attractive forces. The removal of external stresses results in particle rearrangement from relative positions of higher free energy to relative positions of lower free energy as shown by Croney and Coleman (1954) and Schweikle et al. (1974). Blake and Gilman (1970) have suggested that this new interparticle attraction and linkage are resistant to soil slaking.

The resistance to compression

The observed increase in aggregate water stability with ageing, was accompanied by an increase in the resistance of beds of these aggregates to compression (Fig. 2). The data were fitted to eq. (1), with a single exponential term. By replacing the time t with the stress S, eq. (1) becomes

$$D_s = D_f - (D_f - D_i)\exp(-mS) \quad (5)$$

in which D_s is the equilibrium packing density at stress S (kPa). The resulting parameters D_f, $(D_f - D_i)$, and m are given in Table I where it can be seen that the samples which had been aged at constant water content and having the same D_i not only had a lower value of D_f, but also a lower value of m. The change in D_f shows that aged samples are less compressible, and the change in m shows that the increase in packing density with increasing stress occurs more rapidly in non-aged samples than in aged samples.

At a soil water content of W = 15.5%, it is likely that compression occurred as a result of aggregate rupture as has been suggested by Dexter (1975) and Kezdi (1979). Since ageing at constant water content increases the tensile strength of soil aggregates, there will be a corresponding increase in the resistance to compression of beds of the aggregates as predicted by eq. (2).

Further experiments

Further experiments were designed to study whether the result shown in Fig. 2 occurs also when tillage is done at different soil water contents, especially at those close to the optimum soil water content for tillage. Ojeniyi

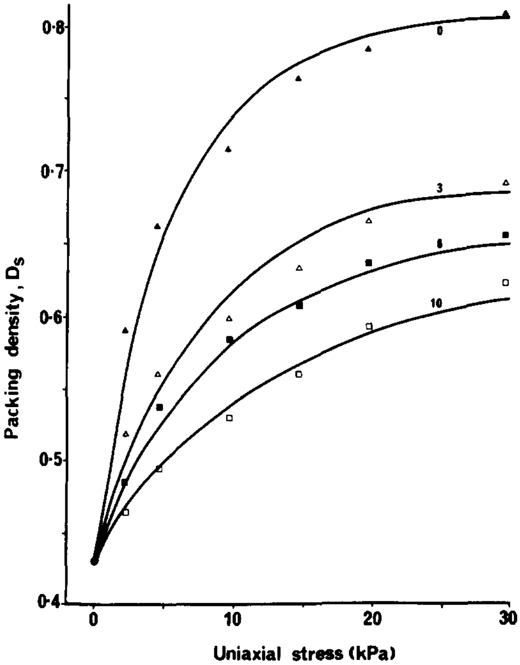

Fig. 2. Effect of ageing (0, 3, 6, 10 days) on the resistance to compression of beds of aggregates of Urrbrae loam. Points are single measurements; the curves are from eq. (5).

TABLE I

Values of D_i, D_f, $(D_f - D_i)$ and m parameters of eq. (5), resulting from compression tests on beds of aggregates of Urrbrae loam aged for different periods of time (± standard errors)

Ageing (days)	D_i	D_f	$(D_f - D_i)$	m (kPa)
0	0.447	0.791 (±0.018)	0.344 (±0.025)	0.191 (±0.045)
3	0.449	0.700 (±0.021)	0.251 (±0.020)	0.109 (±0.028)
6	0.437	0.668 (±0.009)	0.231 (±0.009)	0.108 (±0.013)
10	0.436	0.681 (±0.016)	0.245 (±0.015)	0.053 (±0.007)

and Dexter (1979b) found that the optimum soil water content for tillage of the Urrbrae loam is about W = 17% (or 0.9 of the plastic limit).

In addition, it is interesting to consider Dexter and Tanner's (1974) suggestion that the increase in the resistance to compression results not only in a decrease in the final packing density, but also in an increase in the time to achieve it (the retardation time).

This experiment was done in July and, because of the weather, it was not possible to do tillage exactly at the optimum water content. The soil water content at tillage was 19.3% which is slightly above the plastic limit. At this soil water content, it was difficult to sieve aggregates with the diameter range 1.0—2.0 mm. So, unlike in the previous experiment, the aggregates used in this experiment had diameters in the range 1.0—4.0 mm.

To provide data from another soil exhibiting thixotropic behaviour, an additional experiment was done in October at the Charlick Experiment Station at Strathalbyn. The soil water content at tillage was 19.2% (again slightly above the plastic limit) and, therefore, as in the Urrbrae experiment, the aggregates used had diameters in the range 1.0—4.0 mm. For each of these samples, about 10,000 aggregates were placed in the consolidometer cell and subjected to a rapidly applied uniaxial stress of 29.43 kPa.

The results were fitted to eq. (1) with two exponential terms:

$$D_t = D_f - D_a \exp(-t/\tau_a) - D_b \exp(-t/\tau_b). \tag{6}$$

The resulting parameters D_f, D_a, D_b, τ_a and τ_b are given in Tables II and III for the Urrbrae and Strathalbyn soils respectively (see also Fig. 3).

As expected, the results showed that ageing at constant water contents not only decreases the final equilibrium packing density, but also increases loading time required to achieve a given amount of compression as can be seen by the changes of τ_a and τ_b in Tables II and III. The 2-days aged sample

TABLE II

Values of D_f, D_a, D_b, τ_a and τ_b parameters of eq. (6) resulting from compression tests on beds of aggregates of Urrbrae loam aged for different periods of time. Applied uniaxial stress = 29.43 kPa. (± standard errors)

Ageing (days)	D_f	D_a	D_b	τ_a (s)	τ_b (s)
0	0.644 (±0.001)	0.106 (±0.000)	0.025 (±0.000)	0.8 (±0.3)	28 (±1)
2	0.627 (±0.000)	0.082 (±0.000)	0.013 (±0.000)	5.6 (±0.3)	149 (±18)
4	0.627 (±0.000)	0.079 (±0.002)	0.016 (±0.001)	5.2 (±0.7)	246 (±56)
10	0.603 (±0.001)	0.052 (±0.002)	0.018 (±0.001)	8.0 (±1.0)	384 (±126)

TABLE III

Values of D_f, D_a, D_b, τ_a and τ_b parameters of eq. (6) resulting from compression tests on beds of aggregates of Strathalbyn loam aged for different periods of time. Applied uniaxial stress = 29.43 kPa. (± standard errors)

Ageing (days)	D_f	D_a	D_b	τ_a (s)	τ_b (s)
0	0.657 (±0.001)	0.138 (±0.002)	0.020 (±0.001)	2.2 (±0.2)	194 (±53)
1	0.651 (±0.001)	0.128 (±0.003)	0.025 (±0.002)	3.8 (±0.3)	201 (±70)
3	0.624 (±0.001)	0.105 (±0.005)	0.020 (±0.004)	3.8 (±0.5)	113 (±53)
7	0.617 (±0.000)	0.101 (±0.002)	0.018 (±0.001)	3.2 (±0.2)	213 (±52)
14	0.581 (±0.000)	0.069 (±0.001)	0.013 (±0.001)	3.8 (±0.2)	179 (±41)

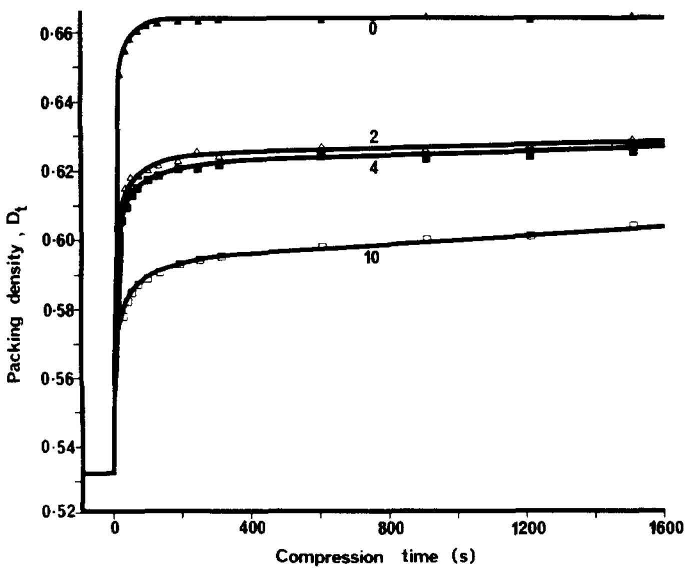

Fig. 3. Effect of ageing (0, 2, 4, 10 days) on the time dependence of the compressibility of beds of aggregates of Urrbrae loam when they are suddenly subjected to a uniaxial stress of S = 29.43 kPa. Points are single measurements; the curves are from eq. (6).

of Urrbrae soil had retardation times of τ_a = 5.6 s and τ_b = 149 s, whereas the 10-days aged sample had retardation times of τ_a = 8.0 s and τ_b = 384 s. For the Strathalbyn soil the retardation times of non-aged samples were τ_a = 2 s and τ_b = 194 s, whereas the retardation times of the 7 days aged sample were τ_a = 3 s and τ_b = 213 s. These values can be put in perspective by considering that a soil is stressed by tractor tyres for about 0.5 s, and by animal feet for 0—100 s (Dexter and Tanner, 1974). Together with the decrease in the final packing density, the observed increases in soil compression retardation times could have some significance in reducing the compaction problem in the field because of the increasing ratio of the retardation times to the loading times with ageing after soil disturbance by tillage. For example, if the data of Table II are used in eq. (6) for a loading time of t = 1 s, it can be seen that ageing the soil for 10 days reduces the resulting packing density from 0.59 to 0.54.

At soil water contents slightly above the plastic limit as used here, it can be expected that compression resulted from plastic deformation as suggested by Day and Holmgren (1952) and McMurdie and Day (1958). At the end of the test it was observed that, in addition to plastic deformation shown by the occurrence of flat interfaces between the aggregates, there was a rupture of some aggregates. Thus it appears that at soil water contents as high as the plastic limit the aggregates disturbed by tillage from Urrbrae and Strathalbyn soil can still exhibit brittle behaviour. Braunack and Dexter (1978) found that even with matric water potentials as small as —1 kPa (about W = 30%), the natural undisturbed aggregates from Urrbrae loam can be made to fail in a brittle mode. Changes in the internal geometry as a bed of brittle aggregates is compressed have been observed and quantified by Braunack et al. (1979).

Plastic deformation only occurs when the applied stress overcomes the shear strength of the soil. Thus, by considering the process by which compression occurs, it can be hypothesized that the increase in the resistance to compression found in these experiments resulted from an increase with ageing after disturbance of the tensile and shear strength of the aggregates. This suggestion is consistent with the concept of aggregate stability changes due to particle rearrangement as discussed above. The increase in shear strength of soil with ageing due to particle rearrangement from relative positions of higher free energy to relative positions of lower free energy has been suggested by Mitchell (1960) and is in accordance with Croney and Coleman (1954) and Schweikle et al. (1974).

CONCLUSIONS

The results of the experiments conducted here demonstrate that in a thixotropic soil, ageing of disturbed aggregates for a few days can increase their water stability. As yet no unique relationship between water stability and resistance to compression of aggregates has been developed. However, it is not unreasonable to suppose that together with the increase in aggregate stability, resulting from an increase in cohesion forces, there is a corresponding increase in the tensile strength, and perhaps also in the shear strength of these aggregates under unsaturated conditions. As has been shown by Mitchell (1960) and Braunack and Dexter (1978) this increase results in an increase of the resistance of beds of these aggregates to compression.

From this result it can be suggested that after tillage a thixotropic soil should be left at constant water content for several days before any other activity is performed or before any forecast of heavy rain. This can reduce both the susceptibility to compaction damage and the risk of aggregate breakdown by water.

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