AGE HARDENING OF AGRICULTURAL TOP SOILS

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Summary

Changes in the strength of remoulded agricultural top soil with ageing are studied for two sandy loam soils from South Australia and a clay soil from Queensland. There is evidence of significant thixotropic behaviour in these soils around the water contents at which tillage is usually performed.

For the Urrbrae soil, in which the dominant clay minerals are illite and kaolinite, the maximum thixotropic strength ratio was obtained at a water content just below the plastic limit. For the Strathalbyn soil, which contains illite and actinolite, and for the Waco soil which contains montmorillonite, the maximum thixotropic strength ratios occurred at water contents between the plastic and liquid limits.

The age hardening for these soils was investigated using probe penetration, tensile strength and compression resistance measurements. The effect was still apparent after sterilization and after removal of organic matter.

Introduction

REMOULDING or shearing an undisturbed soil usually results in a loss of part of its strength. It has been suggested that this decrease in strength is caused by the break down of connecting links and cementing bonds between particles (Winterkorn and Tschebotarioff, 1947). In addition, the change in the energy status in the system resulting from particle rearrangement during remoulding may also be an important factor in this strength decrease (Mitchell, 1960).

When such a remoulded soil is allowed to rest at constant water content, a part or all of its strength may be regained. Skempton and Northey (1952) proposed the term 'part thixotropy' for the first phenomenon, and 'pure thixotropy' for the second phenomenon. The term thixotropy was first used by Freundlich in 1935 to describe isothermal gel-sol-gel transformations in colloid suspensions induced by shearing and subsequent rest (Skempton and Northey, 1952). Burgers and Scott Blair (1948) defined thixotropy as a process of softening caused by remoulding, followed by a gradual return to the original strength when the material is allowed to rest.

The phenomenon of strength regain in a soil is time dependent. Mitchell (1960) therefore defined thixotropy as an isothermal, reversible, time dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest, and softens or liquifies when remoulded. Further, he suggested that the thixotropic process is related to changes in the energy status of the system. When a thixotropic soil is remoulded or compacted, a part of the shearing energy is utilized to disperse the platy clay particles into uniform, parallel arrangement. At this stage the externally applied stress assists the repulsive forces between particles (resulting from double layer interaction) in producing a dispersed system having a lower strength. As soon as the shearing ceases, the externally applied stress, which assists repulsive forces, drops to zero. The net repulsive force is then smaller, and the attractive forces exceed the repulsive forces for the particular arrangement of particles and distribution of water. Consequently, the structure attempts to adjust itself into a new lower free energy arrangement, with a resultant increase in strength. According to this suggestion, a soil exhibits thixotropic behaviour if: firstly, the net interparticle force balance is such that the soil will flocculate if given a chance, and secondly, the flocculation tendency is not so strong that it cannot be overcome by mechanical action, such as shearing or stirring of the soil.

The concept of thixotropic change put forward by Mitchell (1960) is consistent with the ideas of Croney and Coleman (1954), Day and Ripple (1966), and Schweikle *et al.* (1974) who found that shearing or remoulding a moist soil resulted in a less negative value of matric water potential, and subsequent rest resulted in a more negative value of matric water potential. With this result, Schweikle *et al.* (1974) suggested that these changes are a manifestation of clay particle rearrangements from face–face to edge–edge orientation.

Not all increases of strength with ageing result from the thixotropic process. Mitchell (1976) has suggested that thixotropic hardening contributes to the strength regain up to the sensitivity of 8, beyond this value another mechanism must exist. Sensitivity, here, is defined as the ratio of the initial strength to the remoulded strength of the soil. Bjerrum and Lo (1963) suggested that the formation of cementing bonds with ageing may also increase the strength of aged soil. The partial conversion of hydrogen montmorillonite to the aluminium form, which is an active cementing material, has been observed by Mathers *et al.* (1955). Martin (1958) has shown that after ageing for 100 days, lithium kaolinite changes to aluminium kaolinite.

Most previous work on age hardening has been done for civil engineering. The object of the work described here was to study the effect of ageing on the strength of some remoulded agricultural top soils at the water contents at which tillage operations are usually performed. Three different types of soil strength were investigated: penetrometer resistance, tensile strength and compressive strength. The interest was not only in strength increases resulting from thixotropy, but in all processes leading to an increase in the strength of aged, remoulded soil. The separate effects of microbial activity and soil organic matter were isolated by sterilization and oxidation respectively. These effects have received little attention previously. The term *thixotropic hardening* is used only if the conditions of the system met Mitchell's (1960) criterion, otherwise the broader term *age hardening* is used.

Materials and methods

Soil

The soils used were from the 0–10 cm layers of two sandy loams from South Australia, and a clay soil from Queensland. The South Australia soils were Urrbrae fine sandy loam from the Waite Agricultural Research

Institute (34°58′S, 138°38′E) and Strathalbyn sandy loam from the Charlick Experimental Station of the Waite Institute 50 km further south. The Queensland soil was the Waco soil, which is a clay, from Jondaryan.

The Urrbrae soil is a red brown earth, and the Strathalbyn soil is a shallower red brown earth typical of a lower rainfall area (Stace *et al.*, 1968). The Waco soil is a self-mulching montmorillonite black earth mainly derived from tertiary basalt (Coughlan *et al.*, 1973). Some properties of these soils are given in Table 1.

TABLE 1
Composition and Atterberg limits of the soils

Soil	*Proportion of oven dry soil (%)*			*Dominant Clay minerals*	*Plastic limit (%)*	*Liquid limit (%)*
	<20 μm	*<2 μm*	*organic matter*			
Urrbrae	49	17	1.7	illite and kaolinite	19.5	26.5
Strathalbyn	36	12	2.8	illite and actinolite	17.9	30
Waco	87	74	1.9	montmorillonite	54	86

Remoulding

The soil samples were passed through a 1 mm sieve, then remoulded with deionized water at several water contents from slightly below the plastic limit up to nearly the liquid limit. Remoulding was done with a laboratory knife until the soil was as homogeneous as possible. These remoulded soils were allowed to equilibrate overnight, then again remoulded for about 2 min and pressed in plastic containers of 42 mm diameter and 24 mm height.

The strengths of 2–3 cores of each soil at each water content were measured immediately (0 day sample). The remainder, in their containers, were wrapped in thin plastic sheeting and aluminium foil, then stored in a constant temperature room (20 °C) for later testing.

Measurement of soil strength

Soil strength was measured with a motor driven laboratory penetrometer. The probe had a diameter of 1.003 mm, a total tip angle of 60°, and penetrated downward at a rate of 3 mm min^{-1}. This size and shape is commonly used in root growth studies in the laboratory. The force required to penetrate the soil was measured with an electronic balance (Mettler type PC 4400).

Three measurements were done on each core, and so there were 6–9 measurements at each water content for each soil. The strength was calculated as the resistance to probe penetration, Q_P, using the equation

$$Q_P = 4F/\pi d^2 \tag{1}$$

where F is the force required to penetrate the sample at a depth of 5 mm, and d is the probe diameter. This was sufficiently deep to prevent any surface effects from occurring and gave 'steady state' values of penetration resistance.

Each time after testing, the sample was remoulded, pressed back into its container and its strength measured. When this remoulded strength was equal to that of the remoulded sample at the time of preparation (0 day sample), the strength increase was considered to have resulted from thixotropic hardening. Any difference in this remoulded strength would indicate some permanent change, such as the formation of permanent cementing bonds.

After each strength measurement, the water content of the sample was determined. When there had been a significant change in water content, the strength measurement was discarded.

Oxidation and sterilization

In order to determine the separate contributions of soil organic matter and microbial activity to the increase in penetrometer resistance after remoulding, samples of Urrbrae loam were oxidized and sterilized as follows.

Oxidation was with hydrogen peroxide (Robinson, 1922) and sterilization was by mixing the soil with sodium azide and mercuric chloride, 0.5 mg of NaN_3 and 0.5 mg of $HgCl_2\,g^{-1}$ soil as described by Tisdall *et al.* (1978). The ATP test (Jenkinson and Oades, 1979) showed that there was no contamination in sterilized samples.

Water potential changes

Soil water matric potential is governed by soil pore size distribution. In order to test the hypothesis that thixotropic hardening is associated with soil particle reorientation (which would modify the inter-particle pore sizes), measurements were made of soil water matric potential as a function of time after remoulding.

Samples of Urrbrae and Waco soils were remoulded at about 20 per cent and 65 per cent water content respectively. For the Waco soil, remoulding was done with and without sterilization. After equilibration overnight, the soils were again remoulded and compacted in plastic containers of 40 mm diameter and 65 mm height. A tensiometer was inserted into the soil through the middle of the container lid, and the hole on the lid was covered with Silastic 732 RTV sealant to make it air tight. The cores were then stored at 20 °C. Two samples were prepared for each treatment.

Tensile strength

The particle reorientation and cementation which is known to increase soil shear strength should also increase soil tensile strength. The following experiments were done to test this hypothesis.

Samples from the A horizon of the Urrbrae soil were remoulded at 20, 22 and 24 per cent water content, and allowed to equilibrate overnight. These soils were then remoulded again and aggregates with diameter of about 10 mm were made by rolling these remoulded soils by hand.

In the first experiment, the aggregates were aged at the water content at which they were made by storing in plastic containers. These containers were sealed with Silastic 732 RTV sealant, then wrapped in thin plastic sheet and aluminium foil, and stored at 20 °C.

In the second experiment, which was done for the aggregates made at 20 per cent water content only, the aggregates were aged at −100 kP (on pressure plates) and at −20 kPa and −1 kPa (on sintered funnels) also at 20 °C.

Prior to the measurement of strength, all soils of experiments 1 and 2 were dried to the potential of −100 kPa on pressure plates for 2 days. The strength of 16 aggregates of each treatment was measured by crushing the aggregates individually between flat parallel plates until fracture occurred (Rogowski, 1964; Dexter, 1975). The tensile strength, Y, was calculated from

$$Y = 0.576\, F/d^2 \tag{2}$$

where F is the force required to crush the aggregates, and d is the aggregate diameter.

In the second experiment, the water contents at remoulding and at strength measurement after ageing were not the same. The term thixotropic hardening, therefore, is not really applicable. The more suitable term is 'age hardening'.

Compression resistance test

Soil from the A horizon of Urrbrae fine sandy loam was passed through a 1 mm sieve, and then remoulded at 17 per cent water content. The soil was left to equilibrate overnight, and was again remoulded and compacted in a standard consolidometer cell (75 mm diameter, and 14 mm height) to a packing density of 0.672. Packing density, D, was defined as the volume proportion of the soil occupied by solid (mineral) particles:

$$D = \frac{\rho}{\rho_s}\left(\frac{100 - \%\ \text{organic matter}}{100 + \%\ \text{water content}}\right) \tag{3}$$

Here ρ and ρ_s are the dry bulk density of the soil, and the density of solid (mineral) particles respectively.

Compression resistance was measured at 0, 1, 3 and 6 days after sample preparation. The test was done in a standard consolidometer with uniaxial stresses of 0, 4.9, 9.8, 19.6, 29.4 and 49.1 kPa respectively, with 60 min loading time at each level of stress.

To prevent water loss, for the 1, 3 and 6 days aged samples, the consolidometer cell, with the soil inside, was stored in a plastic container, sealed with Silastic 732 RTV sealant, then wrapped in thin plastic sheet and aluminium foil and stored at 20 °C. Two samples were prepared for each period of ageing.

Results and discussion

Effect of water content on soil strength

The effects of water content at time of remoulding on packing density and soil strength are shown in Fig. 1. Unlike packing density, which

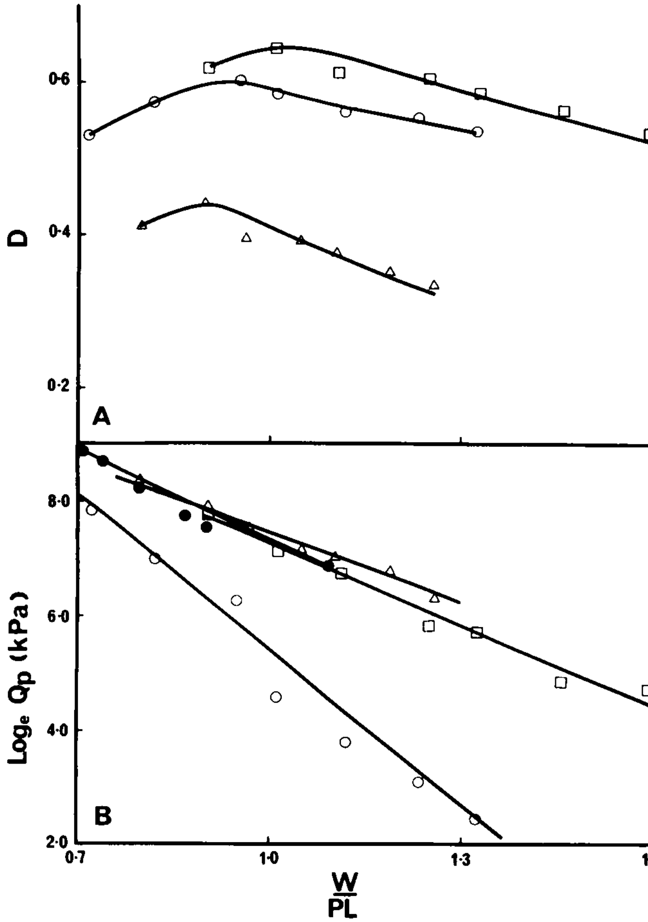

FIG. 1. Effect of water content at remoulding (W/PL) on packing density, D, and penetration resistance, Q_p, of freshly-remoulded Urrbrae (○), Strathalbyn (□), and Waco soils (△), and penetration resistance of 'undisturbed' Urrbrae field clods (●). A. Packing density. B. Penetration resistance (the straight lines are fits of equation 3).

increases with increasing water content up to a maximum value and then decreases on further water content increase, the penetration resistance decreases steadily with increasing water content. The logarithm of the soil strength is an approximately linear function of soil water content (expressed as a proportion of the plastic limit, PL):

$$\log_e Q_p = A - a\left(\frac{W}{PL}\right) \tag{4}$$

over the range of water content used.

The values of the adjustable parameters A and a, together with the strength at the plastic limit, Q_p 1.0, are given in Table 2. For comparison,

TABLE 2

The value of A *and* a *parameters of equation (3) and the strength at a water content equal to the plastic limit* Q_p *1.0, for the freshly-remoulded (0 days' aged) Urrbrae, Strathalbyn and Waco soils, and for the 'undisturbed' Urrbrae field clods. The coefficient of determination is given by* r^2

Soil	A	a	r^2	Q_p 1.0 (kPa)
Urrbrae remoulded	14.75	9.42	0.97	206.4
Urrbrae field clods	12.16	4.77	0.90	1619.7
Strathalbyn	11.88	4.65	0.97	1380.2
Waco	11.81	4.32	0.98	1790.1

the value of the parameters A and a, and of Q_p 1.0, of Urrbrae field clods is also given in Table 2 and Fig. 1. These values were obtained by testing the penetration resistance of clods of about 8–12 cm diameter which were collected approximately 6 months after tillage. These clods were wetted slowly by capillary action, and then dried in sintered funnels or pressure plates to obtain a range of water contents. Six strength measurements were made on each of 6–12 clods as described before.

The penetration resistance of these clods cannot strictly be considered as the strength of undisturbed soil. However, these results provide good evidence that the strength of freshly remoulded soil is much lower, at the same water content, than that of clods which have been exposed to weathering action for about 6 months.

Effect of ageing on soil strength

Ageing of the remoulded Urrbrae, Strathalbyn, and Waco soils increased the resistance of the soil to probe penetration (Tables 3, 4, 5). It was observed that the strength of the samples remoulded after ageing was about the same as that of the 0 day samples. In addition, as shown in Tables 3, 4, 5 the change in water content and packing density of the sample was negligible. Thus the conditions of the system met Mitchell's (1960) criterion for a thixotropic process.

If this explanation is correct, the strength regain with ageing in these soils should be independent of other processes which could contribute to the increase in strength with ageing, such as the formation of cementing bonds caused by microbial activity or organic matter. In separate experiments, the contributions of these two factors were minimised by oxidizing organic matter and sterilizing the Urrbrae soil.

Ageing of both oxidized and sterilized Urrbrae loam resulted in strength increases as shown in Fig. 2. However, the strength of oxidized and sterilized soils, especially for the non-aged sample (0 day), is much lower than that of untreated soil. The oxidized soil at 20 per cent water content shows some interesting features. The strength increase seems to have two components: an initial increase in the first four days or so, and then a larger increase at longer times. We propose that the first increase reflects the true thixotropic process and is due to the reorientation of clay particles, and that the second increase results from inter-particle cementation. It seems

TABLE 3

Effect of ageing on the penetration resistance, Q_p, of remoulded Urrbrae soil

Ageing (days)	*Water content at remoulding (%)*	*Q_p (kPa)*	*Water content after testing (%)*	*Packing density*
0	14	2459.1	14.2	0.534
	16	1099.9	16.4	0.575
	18	591.4	18.2	0.600
	20	103.3	20.0	0.584
	22	42.3	22.0	0.573
	24	22.0	24.1	0.560
	26	12.5	26.0	0.546
6	14	2722.7	14.3	0.540
	16	1880.9	16.2	0.572
	18	976.3	18.0	0.596
	20	131.1	20.0	0.587
	22	65.1	22.0	0.574
	24	23.8	23.9	0.560
	26	12.0	25.9	0.550
12	14	2688.0	14.3	0.536
	16	2054.3	16.2	0.572
	18	1062.4	18.1	0.603
	20	183.5	20.3	0.580
	22	71.6	22.0	0.570
	24	28.8	24.0	0.563
	26	13.3	25.4	0.548

TABLE 4

Effect of ageing on the penetration resistance, Q_p, of remoulded Strathalbyn soil

Ageing (days)	*Water content at remoulding (%)*	*Q_p (kPa)*	*Water content after testing (%)*	*Packing density*
0	16	2443.0	16.3	0.624
	18	1344.3	18.0	0.645
	20	839.8	19.5	0.616
	22	352.6	22.3	0.613
	24	322.5	24.1	0.590
	26	125.6	26.0	0.574
	28	111.3	28.7	0.538
6	16	3703.1	16.6	0.626
	18	2170.4	18.1	0.639
	20	1424.8	20.0	0.616
	22	633.0	22.7	0.611
	24	641.8	23.9	0.586
	26	231.8	26.1	0.570
	28	182.1	28.4	0.538
12	16	4174.8	16.8	0.620
	18	2331.1	18.4	0.647
	20	1561.7	20.1	0.624
	22	708.1	22.6	0.616
	24	650.4	23.7	0.590
	26	245.3	26.1	0.571
	28	193.1	28.2	0.540

TABLE 5
Effect of ageing on the penetration resistance, Q_p, of remoulded Waco soil

Ageing (days)	Water content at remoulding (%)	Q_p (kPa)	Water content after testing (%)	Packing density
0	44	4798.1	43.9	0.410
	48	2494.9	48.4	0.422
	52	1859.4	52.0	0.394
	56	1416.5	56.5	0.390
	60	1160.2	59.7	0.377
	64	864.2	64.0	0.355
	68	620.5	57.3	0.366
6	44	5074.1	44.6	0.410
	48	3900.8	49.3	0.420
	52	3110.1	52.6	0.396
	56	2384.2	56.6	0.392
	60	1954.6	60.2	0.381
	64	1472.4	64.2	0.360
	68	964.6	67.5	0.339
12	44	5026.0	44.2	0.406
	48	3867.0	49.6	0.416
	52	3426.8	52.4	0.390
	56	2783.9	57.2	0.384
	60	2336.8	60.6	0.376
	64	1844.6	64.2	0.358
	68	1031.8	67.2	0.343

likely that the presence of organic matter may cause cementation to occur much more slowly. This would account for the greater rate of increase in the strength of the oxidized soil after five days. Quirk and Panabokke (1962) showed that the crushing strength of natural aggregates from a virgin plot of the Urrbrae soil (2.7 per cent organic matter content) was greater than that of aggregates from a cultivated plot (1.3 per cent organic matter content) over the range of water contents they used. The crushing strengths of remoulded cores prepared from these two soils, however, were almost identical. For this phenomenon, they reasoned that the differences in strength of the field aggregates could not be attributed to soil organic matter content as such but rather to the disposition of the organic matter in the soil. Becher (1978) found that the penetration resistance of soil cores prepared from Pelosols decreased with increasing organic matter content over a range of water content. For natural aggregates, at water potentials less negative than −4 kPa the penetration resistance increased with decreasing organic matter content, whereas in drier soil the increase in organic matter content did not give a consistent effect. The results shown in Fig. 2 cannot be compared directly with this earlier work, because here the organic matter content of oxidized sample was practically zero, whereas in the samples of either Quirk and Panabokke (1962) or Becher (1978), all the soil samples contained some organic matter.

Evidence of thixotropic behaviour in the absence of organic matter has also been found by Blake and Gilman (1970). In studying the change in

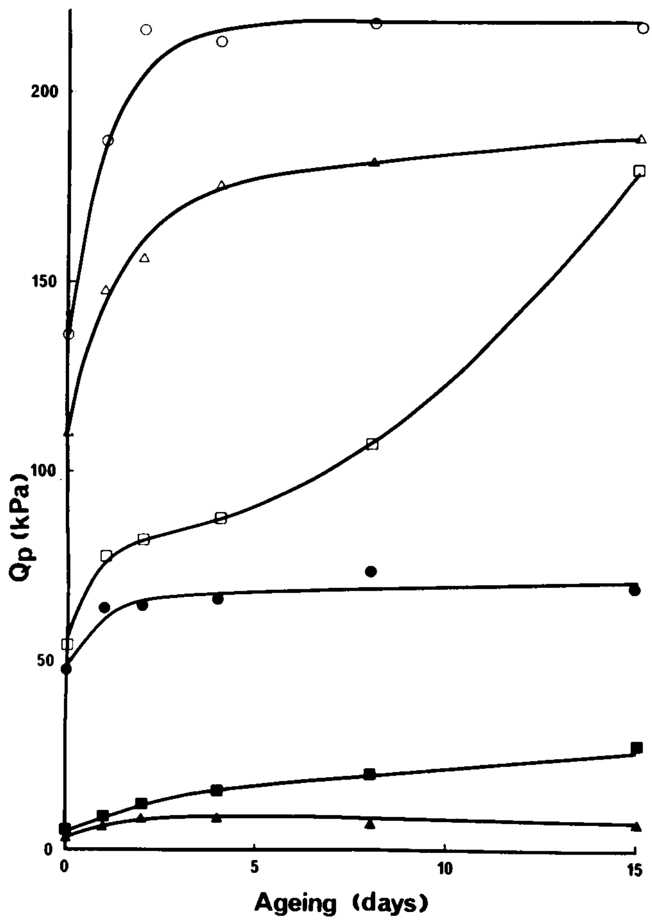

FIG. 2. Effect of ageing on the penetration resistance, Q_p, of the Urrbrae soil. (○) control 20 per cent water content; (●) control 22 per cent water content; (□) oxidized 20 per cent water content; (■) oxidized 22 per cent water content; (△) sterilized 20 per cent water content; (▲) sterilized 22 per cent water content.

the water stability of newly formed aggregates, which was suggested to be analogous to a thixotropic hardening in compacted soils, Blake and Gilman (1970) found that the increase in water stability of newly formed aggregates was independent of organic matter. Abrukova (1971) found that in thick chernozem soils, thixotropic behaviour was absent in the sample from the top 10 cm layer which contains high organic matter, but occurred in the samples from the 80–90 cm and 150–160 cm layers. However, it is likely that other important factors, besides organic matter, would have differed over this range of depths.

As discussed previously, thixotropic behaviour is related to the changes in the energy status of the system. Thus, if the strength regain found in this

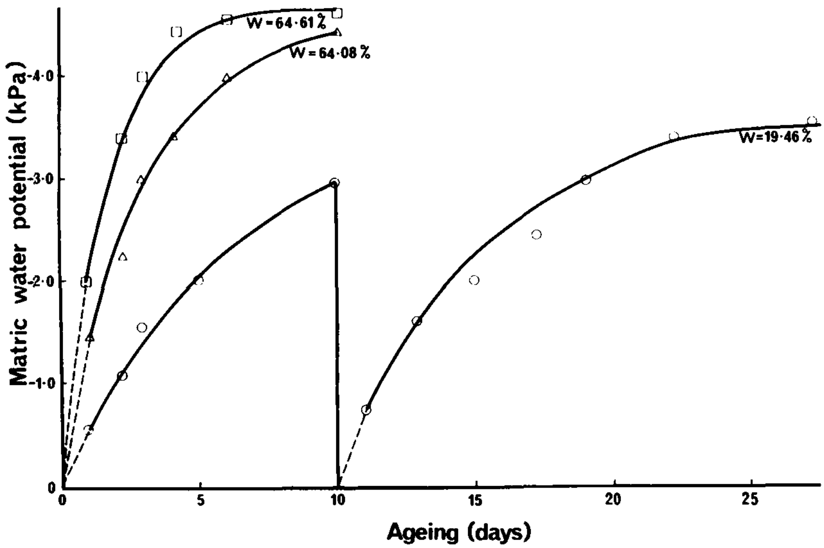

FIG. 3. Effect of ageing on matric water potential of remoulded Urrbrae (○); Waco unsterilized (□); Waco sterilized (△) soils.

experiment was a thixotropic process, ageing should influence soil matric water potential. To study this, an experiment on the effect of ageing on matric water potential was carried out.

The result (Fig. 3) shows that ageing of the remoulded Urrbrae and Waco soils results in a more negative value of matric water potential, and subsequent remoulding makes the matric water potential less negative. This shows that remoulding the Urrbrae and Waco soils at the water contents used results in a high relative free energy condition, and subsequent rest decreases the free energy of the system which leads to an increase in strength.

To examine the effect of water content at remoulding and compaction on thixotropic strength regain, the term 'thixotropic strength ratio', TSR, was used. This is defined as the ratio of the strength of an aged sample to that of a non-aged or freshly-remoulded sample. The effect of water content on TSR, calculated from the results given in Tables 3, 4 and 5 is shown in Fig. 4 for 12 days of ageing.

For the Strathalbyn and Waco soils, TSR increased with increasing water content from below the plastic limit to above the plastic limit, and then decreased at higher water contents. Thus, the peak value of TSR occurred at water contents between the plastic and liquid limits. For the Urrbrae soil, however, the highest value of TSR was obtained at water content just below the plastic limit.

Moretto (1948) and Skempton and Northey (1952) found that thixotropic strength regain of natural clays decreased with decreasing water content from the liquid limit. Skempton and Northey (1952) even suggested that thixotropic strength regain at water contents close to or at the plastic limit might be zero. Mitchell (1960), on the other hand, found that thixo-

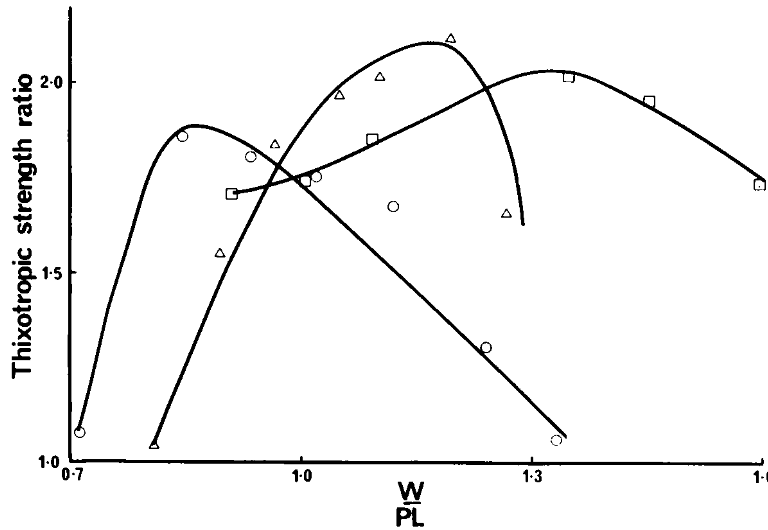

FIG. 4. Effect of water content at remoulding on thixotropic strength ratio of the Urrbrae (○); Strathalbyn (□), and Waco (△) soils after 12 days ageing.

tropic strength regain in compacted soil occurred also at water contents below the plastic limit. With a soil of 25 per cent plastic limit and 39 per cent liquid limit, he showed that at 21 per cent water content the TSR was about 1.1–1.4 depending on the strain system used to measure the strength. Further, he showed that the TSR increased with increasing water content up to W = 28 per cent, and then decreased at higher water contents.

The result found for the Strathalbyn and Waco soils was similar to that of Mitchell (1960). Mitchell's (1960) explanation, therefore, might be valid for these soils. It was suggested that at low water contents the soil is strongly flocculated due to double layer water deficiency, and therefore thixotropic strength regain would be negligible. At high water contents, the soil disperses on its own accord from high double layer repulsion. Consequently, thixotropic hardening is insignificant. At intermediate water contents, the structure may be made dispersed through the application of shear strain, and when this shear is released the soil is able to flocculate on its own accord with a consequent strength increase.

As shown in Fig. 4, the highest value of TSR for the Urrbrae soil was obtained at a water content below the plastic limit. This is not unusual. Seed and Chan (1957), with a soil of 23 per cent plastic limit and 37 per cent liquid limit, found that thixotropic hardening ratio increased with increasing water content from 15 to 18 per cent, and then was about constant at water content 18 to 20 per cent. Using the Vicksburg silty clay (26 per cent plastic limit and 34 per cent liquid limit), Gray and Kashmeery (1971) found that the maximum TSR occurred at about 22 per cent water content.

The high strength regain at low water content for the Urrbrae soil can probably be explained in terms of the type of clay minerals in this soil. Aylmore (1960) found that the clay minerals in the Urrbrae soil were illite

TABLE 6

Effect of ageing on the tensile strength of remoulded aggregates of Urrbrae soil

Ageing (days)	Tensile strength (kPa)					
	experiment 1			*experiment 2*		
	$W = 20\%$	$W = 22\%$	$W = 24\%$	-100 kPa	-20 kPa	-1 kPa
0	15.9	16.0	16.1	15.3	15.3	15.3
3	—	—	—	18.3	16.3	16.2
4	20.3	18.5	15.5	—	—	—
6	—	—	—	25.5	20.3	15.9
LSD 5%:		1.53			1.98	

(60 per cent) and kaolinite (40 per cent). Cashen (1966) has found that for kaolinite, thixotropic behaviour exists at low water content. At high water contents this clay has a dilatant property as shown by the fact that shearing this clay results in a more negative value of matric water potential. Consequently, ageing would not increase the strength, and might decrease the strength as shown by George (1967).

It has been suggested that during thixotropic changes, the arrangement of clay particles in the matrix changes from face–face to edge–edge orientation (Schweikle *et al.*, 1974). If this is so, the tensile strength, which is a measure of interparticle cohesion (Ingles, 1962) should increase with ageing. Two experiments were done to test this hypothesis.

The results given in Table 6 show that the tensile strength of remoulded aggregates increased with ageing. A significant increase in the tensile strength occurred only at 20 to 22 per cent water content (for the first experiment), and at −100 kPa potential ageing (for the second experiment). This was in good agreement with the result given in Fig. 4 which shows that the strength regain with ageing for the Urrbrae soil does not occur readily at high water contents.

Compression resistance

To analyse the results of the compression test, the packing density was plotted against the applied stress. The resulting data are shown in Fig. 5 and were fitted to

$$D_S = D_f - D_m \exp(-S/m) \qquad (5)$$

where D_s is the packing density at stress S, D_f is the final equilibrium packing density, and D_m and m are adjustable parameters to be determined.

The result shows that ageing results in a decrease in the values of D_f and D_m and an increase in m (Table 7). The small value of D_f indicates that with the same applied stress, aged samples compress less than non-aged sampled. A larger value of m indicates that the increase in packing density with increasing applied stress in aged samples occurs more slowly than in non-aged samples. This indicates that ageing increases the resistance of Urrbrae loam to compression.

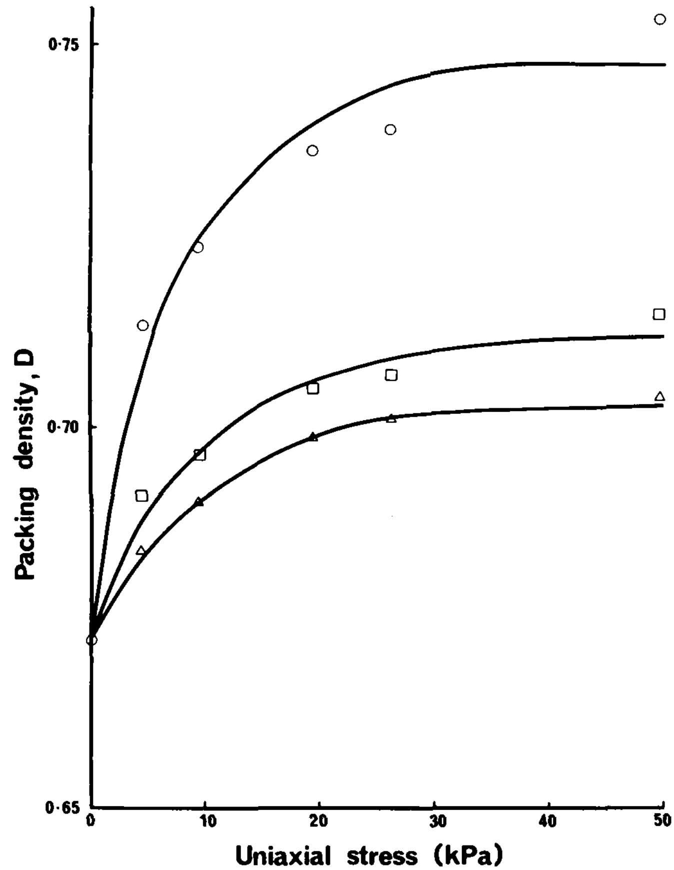

FIG. 5. Effect of ageing on the stress dependence of the compression resistance of Urrbrae loam. Measurements are given by: (○) non-aged; (□) 1 day; (△) 6 days, and the curves are fits of equation 5.

TABLE 7

The value of D_f, D_m, *and m parameters of Equation (5) resulting from compression tests on remoulded Urrbrae soil aged for different times*

Ageing (days)	D_f	D_m	m
0	0.747 (±0.006)	0.072 (±0.008)	8.34 (±3.00)
1	0.712 (±0.003)	0.039 (±0.003)	10.91 (±3.38)
3	0.714 (±0.003)	0.041 (±0.003)	15.04 (±4.06)
6	0.704 (±0.000)	0.032 (±0.000)	11.81 (±0.74)

It has been suggested that at high water content the compression of aggregated soil occurs as a result of plastic deformation (McMurdie and Day, 1958; Davis *et al.*, 1973). At low water content, the compression occurs as a result of aggregate rupture (Dexter, 1975). Plastic deformation occurs when the applied stress overcomes the shear strength of the soil, and aggregate rupture occurs when the applied stress overcomes the tensile strength. Since ageing increases the shear strength (Mitchell, 1960) and the tensile strength, it is reasonable that ageing results in an increase in compression resistance. An increase in the compression resistance with ageing has also been shown by Mitchell (1960).

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