THE EFFECTS OF WETTING AND DRYING ON SOIL PHYSICAL PROPERTIES

A thesis submitted by

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for the degree of
Doctor of Philosophy

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December 1980.

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SUMMARY

Physical factors responsible for aggregate formation and stability, and methods for assessing aggregate water stability are reviewed. The natural factors responsible for developing and controlling soil strength, which is defined as the ability of a soil to withstand an applied stress, and methods of soil strength measurement are also reviewed.

Thixotropic hardening

This topic does not really fall within the subject title of this thesis. However, this study is a precursor to the studies of the effects of wetting and drying cycles because it is necessary to be able to avoid any confounding effects of thixotropic hardening, especially with remoulded and disturbed soil samples.

It is found that some agricultural top soils exhibit appreciable thixotropic behaviour at soil water contents close to that at which tillage is usually performed. This is shown by increases in the strength (shear strength, tensile strength, penetration resistance, and compression resistance) with ageing at constant water content.

The water content at which maximum thixotropic strength regain occurs is influenced by the clay mineral content of the soil. For soil containing kaolinite, the maximum thixotropic strength regain occurs at a water content at about or below the plastic limit. For soil containing illite and montmorillonite (no kaolinite) this maximum value occurs at the water content between the liquid and plastic limits.

Effect of wetting and drying on aggregate formation and stability

Planes of weakness (cracks) formed by unequal swelling and shrinkage resulting from uneven wetting and drying provide the initial faces of

soil aggregates in an initially unaggregated soil. It was found that wetting and drying to water matric potential of -1 kPa and -100 kPa, and of -1 kPa and 60°C oven dried resulted in the greatest aggregation (> 0.25 mm).

For aggregated soil too, wetting and drying influences aggregate water stability. Providing there is an extra energy source for microbial activity (such as in aggregates disturbed by tillage), wetting and drying first increases the proportion of water stable aggregates > 0.5 mm to a maximum value. Further wetting and drying then decreases aggregate water stability. When there is no extra energy sources, wetting and drying steadily decreases aggregate water stability.

Effect of wetting and drying on soil strength

Wetting and drying may influence the strength of a soil. Providing the stresses set up by unequal swelling and shrinkage are able to create cracks, wetting and drying decreases the tensile strength of remoulded aggregates and of the aggregates disturbed by tillage. For larger aggregates (clods) the decrease in the strength was shown by the fact that with the same amount applied energy (by the drop shatter test or by a second implement pass) greater soil break up occurred.

Since soil wetting and drying in the field are usually from one side only, the formation of cracks in larger aggregates occurs much more readily than in smaller aggregates. As a consequence, the decrease in the strength in larger aggregates occurs much more rapidly than that in the smaller aggregates. This phenomenon led to the development of a method for measuring soil friability.

Soil friability is defined as the tendency of an unconfined soil mass to break up and to crumble under applied stress into smaller mechanically stable soil aggregates. A measure of soil friability was developed from the theory of the brittle fracture theory of soil aggregates. Friability was obtained from the slope, k, of plots of the log aggregate tensile strength, σ_T, against the log aggregate volume, V:

$$\log_e \sigma_T = K - k \log_e V.$$

Values of friability ranged from $k < 0.05$ (not friable) to $k > 0.40$ (mechanically unstable).

This measure can be used to predict the water content at which tillage can produce the greatest soil crumbling. The method is also useful in explaining the results of some earlier workers, and may have a very interesting future in the study of soil physical properties.

Application of soil conditioners

Phosphoric acid addition decreases the tensile strength of remoulded and natural aggregates, but increases the penetration resistance of remoulded soil. As a consequence of the decrease of aggregate tensile strength, phosphoric acid application decreases the resistance of beds of these aggregates to compression. Phosphoric acid is also found to increase soil friability.

Calcium sulphate addition increases the tensile strength of remoulded and natural aggregates, but decreases the penetration resistance of remoulded soil. This increase in aggregate tensile strength results in increases in the resistance of beds of these aggregates to compression.

Effect of tillage on soil water behaviour

The amplitude of natural soil water content flucutations (wetting and drying) in the tilled layer of a tilled soil is greater than that at the same depth in an untilled soil. Under South Australian conditions, the cumulative wetting and drying in the tilled soil (0 - 10 cm depth) until 20 days after tillage was greater by a factor of 1.7 - 2.0 than that in untilled soil. For the 0 - 3 cm layer, these values ranged from 3.1 - 5.6 depending on the tillage system.

Meteorological factors influence the rate of drying from a soil when soil water content is high enough to provide the evaporative demand. When soil water content is low (for the Urrbrae soil, lower than about 10%), the rate of drying is mainly controlled by soil water content.

Agricultural implications

Cracks are formed by natural wetting and drying. These make the soil weaker, and at the same time provide initial faces of soil aggregates. This could have some significance in soil management practice. By increasing the amplitude of wetting and drying, by for example stubble management, it is likely that the soil can be tilled more esily and can result in a finer tilth.

Tillage increases the amplitude of wetting and drying, the strength of the clods produced by tillage decreases with wetting and drying, and at the same time aggregation is promoted by wetting and drying. It is therefore suggested that delaying a second implement pass for several days after a first implement pass, can enable soil to be tilled with minimum energy and cost to produce a fine seed bed. In addition, with decreasing clod strength it is possible to reduce the number of implement passes so that compaction damage can be minimized. Compaction damage might also be reduced as a result of the increase in the tensile strength (with a delay of the second implement pass), and hence compression resistance, of aggregates in the deeper part of the tilled layer.

Thixotropic hardening of top soil may influence seed germination and crop growth, either directly through the increase in strength or indirectly through its effect on soil water behaviour.

It is suggested that phosphoric acid should be used in soils of high aggregate tensile strength, because besides increasing aggregate water stability it also reduces aggregate tensile strength and increases friability. Calcium sulphate, on the other hand, should be used in soils of low aggregate tensile strength, so that besides increasing aggregate water stability, the resistance of the soil to compression can be increased.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of author's knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Wani H. Utomo

December, 1980.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. A.R. Dexter, Senior Lecturer in Soil Science, and to Dr. J.M. Oades, Reader in Soil Science and the Chairman of the Department, for their guidance and helpful discussion during supervision of this project.

My thanks also go to the Dean of Agricultural Faculty of Brawijaya University and the Rector of Brawijaya University who gave me permission to leave my duties so that I could undertake this project.

The assistance of David Hein and Terry Sherwin with several of the experiments is gratefully acknowledged.

Dr. W.W. Emerson of CSIRO Division of Soils assisted with the consolidometer test.

M. Ahmed helped with the ATP determination.

Dr. J.S. Hewitt assisted in the development of theory accounting for errors resulting from a random measurement (appendix).

The assistance of Biometry Section staff, especially Dr. P. Baghurst and T. Hancock, is gratefully acknowledged.

The thesis was typed by Joan Howe. Joy Willis helped with the preparation of the figures.

I was sponsored by Australian Government through the AVCC-AAUCS scholarship.

At last, but not least, my deep gratitude go to my wife, Titiek, and my sons, Iwan and Dodi, for their continuous support, understanding and encouragement.

SECTION 1. INTRODUCTION

Soil, which is defined as the loose top layer of the earth, is virtually the sole source of man's sustenance because it supports the plants and animals which provide food, fiber, and shelter. Throughout the ages man has primarily been an exploiter of the soil and its resources without much regard for its conservation or long-term management. Soil is a non-renewable resources, and it has often fallen into decline and in many places eventually disappeared.

It is now, although rather late, essential for us to learn how to manage the soil correctly. With increasing population and its consequent demands, we are being forced to make the soil as productive as possible whilst at the same time preventing it from being depleted further. To attain these objectives, soil management systems must be developed which allow the production of food crops at minimum cost, and which at the same time, minimize soil deterioration caused by unnecessary removal of plant nutrients, erosion, and compaction.

Much work has now been done to study and to attempt to find the optimum methods for managing a soil. These include tillage, minimum or zero tillage, cropping system, crop residue management, and the use of chemical conditioners. History has proved that while we have been successful in our attempts to increase crop yield per unit area on good soil, we have fallen behind in our attempts to maintain the condition of the soil. One of the reasons for this is probably the lack of information on the effects of different soil management systems on soil physical properties. Where there is information, it is often shown separately, and very little effort has been made to integrate the data with other knowledge or to relate it to soil management practice.

The concept behind the project described in this thesis was that any work done to a soil which modifies its condition would be likely to influence the physical properties of the soil. The changes in these physical properties might have some significance in the management of the soil by enabling a reduction in the input cost of the work and/or by reducing the rate of soil deterioration in crop production.

The first aspect considered was the influence of changes in soil water content and soil temperature fluctuations resulting from soil management practices (such as tillage or crop residue management) on other physical properties of the soil. In the case of an increase in these fluctuations (especially of soil water content), there might be formation of cracks in the soil. Such cracks would enable the soil to be more easily broken by the mechanical impact of tillage implements. If this were so, the input energy and cost involved in the preparation of seed beds could be reduced. In addition, with decreasing soil strength due to crack formation, it might be possible to reduce the number of implement passes, and hence reduce the compaction caused by the vehicle wheels.

Any change in soil water content fluctuation might also have some significant effect in the formation and stabilization of soil aggregates. If this suggestion were correct, then soil aggregate management, and thus also some soil erosion control, could be achieved by modifying the soil water content fluctuation regime.

The second aspect considered was the possibility of increasing soil strength with time after the soil is broken up by tillage. It is well known, especially in the field of civil engineering, that disturbing or remoulding a soil results in a decrease in its strength, and allowing this soil to rest at constant water content can result in the recovery of all or part of the strength. Since tillage and/or other soil disturbance usually involves some shearing and remoulding, then allowing this soil to rest for several days may increase the strength of this disturbed soil. In the case of an increase in the soil water content fluctuation, which mostly occurs in the top layer of the disturbed soil, such increases in strength may not occur. Any increase would be expected to occur mainly in the deeper layers where soil water content fluctuations are much smaller. Any increase in strength in these layers could reduce the susceptibility of the soil to compaction damage.

In the past, chemical soil conditioners for agriculture have usually been studied in terms of their effects on the water stability of soil aggregates. It was thought that the use of chemical soil conditioners might affect other physical properties of the soil, especially strength. If this were true, it might be worthwhile to increase or decrease, which ever is necessary, soil strength with the conditioners in order to obtain an additional benefit from soil conditioner application.

To study these suggestions, a series of laboratory and field experiments were carried out and the results are discussed in this thesis. The laboratory experiments were aimed to investigate: effects of ageing at constant water content on the strength of remoulded agricultural top soil; influences of chemical treatments on strength changes with ageing; effects of wetting and drying cycles on the formation and water stability of soil aggregates; and effects of wetting and drying cycles and temperature cycling on soil strength.

Field experiments were carried out to test the results of the laboratory experiments under natural conditions, and in particular to determine: the extent to which tillage modifies soil water content fluctuations; consequences of these modifications on the physical properties of clods and aggregates in the tilled layer, especially clod and aggregate strength and aggregate water stability; and effects of ageing at constant water content on the water stability and the resistance to compression of aggregate beds of aggregates disturbed by tillage. In these experiments, the importance of meteorological factors in determining soil drying is also considered.

It is expected that the results of these investigations could ultimately lead to the development of improved systems of management of surface soil based on physical and environmental principles.

SECTION 2. REVIEW OF LITERATURE

2.1 The physical agents responsible for aggregate formation and stability

Soil structure has been defined as the arrangement of individual mechanical separates, soil aggregates which are formed by aggregation of smaller mechanical fractions, and accompanied pore space into a certain structural pattern (Baver, Gardner, and Gardner, 1972). In tillage practice, the term clod and aggregate are used to describe the aggregation of small soil fractions into larger structural units. In this thesis, the term clod is used to describe a structural arrangement with dimensions of several cm, and the term aggregate is used to describe that with dimensions of up to several mm.

Considerable attention has been given to the study of soil structure, and excellent reviews have been published by Martin *et al.* (1955), Marshall (1962), Harris, Chesters and Allen (1966), and more recently by Sequi (1978). Most of these reviews, however, are centered on the role of chemical and biological processes in the development and stabilization of soil aggregates. Relatively little attention, except by Harris *et al.* (1966), has been given to the role of physical agents either in the formation or stabilization of soil aggregates.

The term physical agents used in this thesis includes the action of weather, especially wetting and drying cycles and freezing and thawing cycles, and mechanical action as produced by tillage. Before discussing the role of these agents in the formation and stabilization of soil aggregates, it is worthwhile to discuss the assessment of aggregate stability.

2.1.1 Assessment of aggregate stability

The stability of soil aggregates in water is the main interest in studying the physical properties of soil. Water stable aggregates are necessary to maintain soil aeration and water conductivity to provide a favourable condition for growing crops. The existence of water stable aggregates is also important in erosion control.

When a dry soil aggregate is immersed in water, it may breakdown into smaller soil fragments. Several processes may be involved in this phenomenon, namely (1) decrease in the cohesion due to weakening of cementing bonds, (2) unequal swelling of the soil mass, (3) internal pressure originating from entrapped air. The importance of these factors in causing aggregate breakdown will be discussed further in section 2.1.2.

The most widely used method to assess aggregate water stability is probably the wet sieving method developed by Yoder (1936), which is actually the modification of Tiulin's (1933) method. Several modifications have been proposed to improve the reliability and reproducibility of this method. An excellent discussion and bibliography on this subject has been published by Kemper and Koch (1966). In principle, the measurement of aggregate water stability by this method can be described as follows.

A given amount and size of soil aggregates are put onto sieve or a series of sieves with a given opening size. The sieve(s), with the aggregates on it(them), are immersed in water for a given time, then shaken up and down in water at certain speed and for a standard time. Aggregates which are left on each sieve after wet sieving are oven dried, and then weighed.

The result can be expressed as the percentage of the initial total weight remaining in aggregates larger than any given diameter, such as 0.10 mm (Baver and Rhoades, 1932), 0.25 mm (McHenry and Russell, 1943; Willis, 1955), 0.5 mm (Bryant, Bendixen and Slater, 1948), and even 3.0 mm (Low, 1954), or in mean weight diameter (MWD) or geometric mean diameter (GMD) of the aggregates left in the sieves after wet sieving.

To calculate the mean weight diameter (MWD), van Bavel (1949) plotted accumulated frequency which was obtained by summing the percentage (by weight) of aggregates retained at any given size, against the upper limit of separation. The MWD was obtained by calculating the area over the curve. This can be done either directly by counting the area (of small unit graph paper), or by using a planimeter on the curve. Cornfield (1955) pointed out that although this method was very useful, it was time consuming. To overcome this problem, Youker and McGuinness (1957) proposed a simple regression method. The cumulative percent (by weight) was plotted against the size of sieve opening. Unlike van Bavel (1949), however, the plotted points were joined by straight lines. The area above the straight lines were calculated by two methods, i.e. (1) by counting this area as done by van Bavel (1949), and (2) by accumulating the products of multiplication of the class mid points and the percent retained. A least square regression line was computed from these measurements and resulted in

$$Y = 0.876\,x - 0.079 \qquad (2.1)$$

where Y is the mean weight diameter, and x is a constant which is obtained by summing the multiplication product of mean sieve size and percent retained. This method has been successfully used in tillage experiments by Bateman, Naik and Yoerger (1965) and Bushan and Ghildyal (1971, 1972).

The use of geometric mean diameter (GMD) in studying the water stability of soil aggregates was developed by Mazurak (1950). To obtain

GMD, the weight of aggregates in a given size fraction was multiplied by the logarithm of the mean diameter of that fraction. The sum of these products for all size fractions were divided by the total weight of soil sample. Logsdail and Webber (1959) used this method of presentation in a study of the effects of freezing and thawing on aggregate water stability of Haldiman clay.

The most important factors in the wet sieving method are the pretreatment of the sample, and the mechanical operation of the machine, such as the frequency, amplitude, and time of sieving. A lot of workers have recognized the importance of standardization of the wet sieving method (e.g. Russell, 1971). A standard method, however, has not yet been established. Each workers chooses his own interest according to the nature of the soil and the objective of the study. Because of this, it is necessary to describe sample pretreatment and mechanical operation of the machine in presenting the results of such a test.

It has been found that the results of wet sieving are influenced by the initial size of soil aggregates (Woodburn, 1944; Low, 1954), the initial water content of soil aggregates (Low, 1954; Panabokke and Quirk, 1957), method or rate of wetting (Emerson and Grundy, 1954; Panabokke and Quirk, 1957), method of aggregate storing (Evans, 1948; Hoffman, 1976), temperature of water in which wet sieving is done (Woodburn, 1944; Low, 1954), the time (season) of soil sampling (Slater and Hopp, 1951; Stefanson, 1971), and of course the mechanical operation of the machine.

The surface soil structure under natural conditions is subject to the impact of falling rain drops. With this idea, McCalla (1942) developed the method of aggregate water stability determination based on the amount of energy necessary to destroy soil aggregates. Drops of water approximately 4 mm in diameter falling from 0.5 m height from a burette at the same rate, were allowed to strike moist soil aggregates of 4 mm diameter resting on a 1 mm sieve. The kinetic energy, E, was calculated from

$$E = 0.5\, m\, v^2 \qquad (2.2)$$

where m is the mass of the water, and v is the terminal velocity.

In a later study, McCalla (1944) used the number of drops instead of the kinetic energy. He found that a water drop height of 0.3 m height (v = 2.5 m/sec.) and a soil aggregate size of 0.15 g were satisfactory for studies of Peorian loess sub-soil and Marshall silty clay loam top soil.

Smith and Cernuda (1951) noticed that most soils of Puerto Rico are clays and often tend to break into rather distinct aggregates of somewhat similar size. They, therefore, suggested that the water drop test developed by McCalla (1942; 1944) would be suitable to assess the water stability of soil aggregates of these soils. It was found that 1.0 g aggregates, a drop size of 1.0 ml from 0.6 m height (v = 3.35 m/sec.), and an application rate of 1 drop per second were suitable for these soils.

Pereira (1955) considered that the problem in the water drop test was to obtain very small but representative samples from fields which are mostly nonhomogenous. To overcome this problem, he used a rainfall simulator instead of single water drops, and soil cores, instead of single soil aggregates. The use of rainfall simulators, especially to study run off and soil erosion, has lately been received much attention (Meyer and McCune, 1958; Mazurak and Mosher, 1970; Grierson and Oades, 1977).

Emerson (1967) developed a water coherence test for use in assessing the stability of soils for earth dam construction. Thus this method is mainly applied to sub-soils, and is based on the swelling, slaking, and dispersion behaviour of soil aggregates when immersed in water. To do this, soil aggregates are immersed in distilled water, and according to their behaviour, the aggregates are classified into eight classes (Figure 2.1).

Loveday and Pyle (1973) modified the Emerson dispersion test as part of a study of soil hydraulic conductivity. The Emerson dispersion test has also been successfully used by Greenland, Rimmer and Payne (1975) to determine the structural stability of top soils of English and Welsh soils. This method has been found to be very useful in assessing drainage problems in these soils.

Low (1954) and others (Rovira and Greacen, 1957; Richardson, 1976) used dispersion ratio as an index of aggregate water stability. The dispersion ratio is defined as the ratio of percent silt plus clay obtained after weak dispersion to that obtained after complete dispersion during mechanical analysis. Rovira and Greacen (1957) used the weak dispersion method developed by Marshall (1956). This method consisted of measuring with a plummet balance the amounts of material smaller than 50 μm after successive periods of end-over-end shaking. A suspension of about 20 g of soil in 1 l of water was used.

The change in permeability due to leaching with dilute salt solution has been proposed by Emerson (1954; 1955) as a measure of aggregate water stability. The method consisted of replacing all other exchangeable ions of 20 g of natural air dry 1 - 2 mm soil aggregates with sodium, and then measuring the decrease in the permeability of the aggregate bed when brought into equilibrium with successively more dilute solutions of sodium

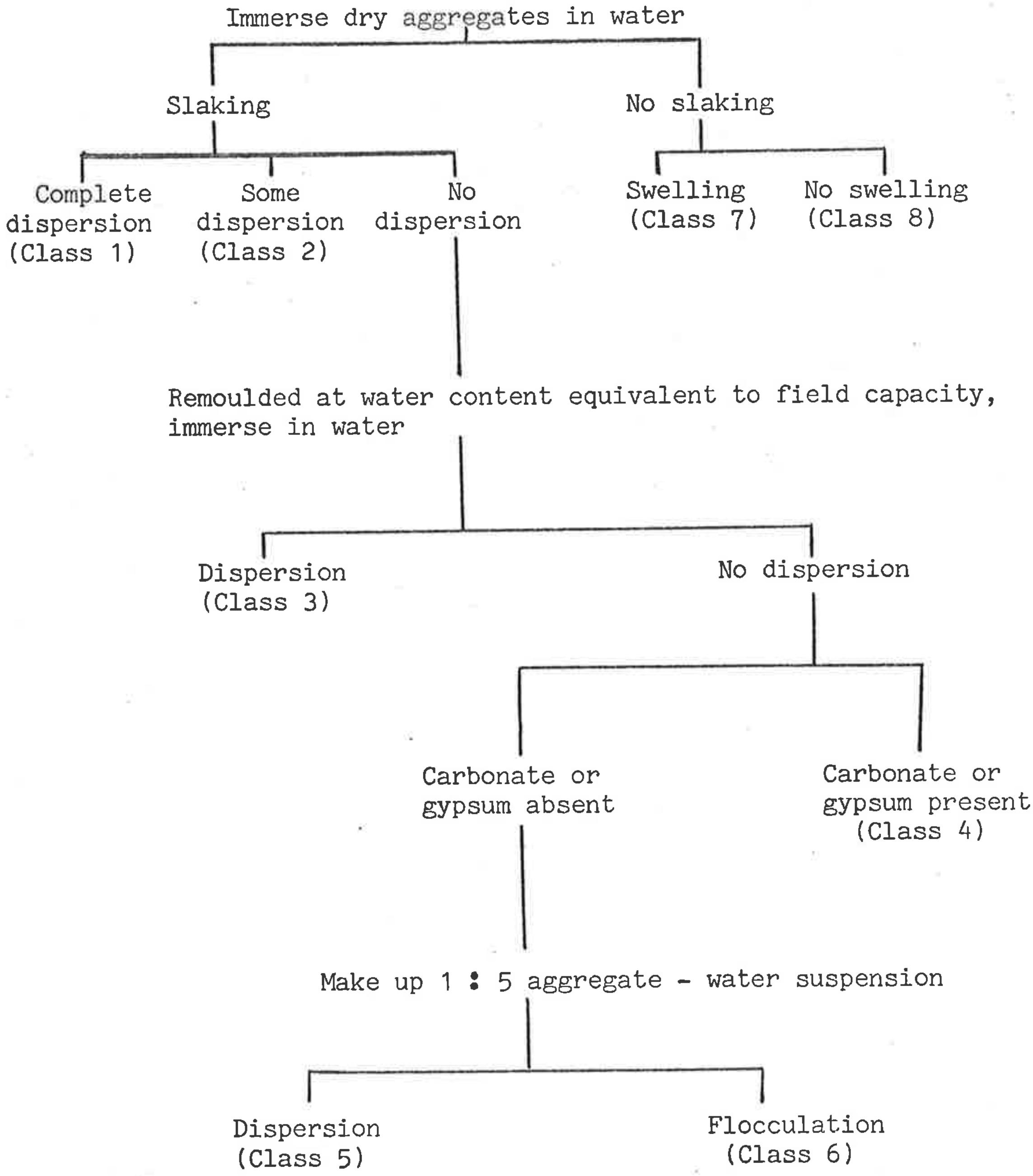


Fig. 2.1. Scheme for determining class numbers of aggregates (Emerson, 1967).

chloride. This method then was modified by Dettmann and Emerson (1959) and used to study the effect of cropping system on aggregate water stability. A 1 cm thickness of soil aggregates (1 - 2 mm diameter) was supported on a 1 cm layer of glass spheres (0.5 - 1 mm diameter), and the permeability was measured by percolation of 0.5 N NaCl. The permeability found in this test was denoted as K_1. Then 3 l of the same solutions were percolated for 24 hours, after which the permeability measurement was repeated, and the value found in this test was referred to as K_2. The ratio of K_2/K_1 was regarded as a measure of cohesion.

2.1.2 Wetting and drying cycles

Alternate wetting and drying causes swelling and shrinkage of soil. These volume changes have for a long time been implicated in both the formation of and changes to soil aggregates (Bouyoucos, 1924). With a bentonite-sand mexture, McHenry and Russell (1943) found that wetting and drying up to 20 cycles increased the formation of soil aggregates larger than 0.25 mm. They suggested that each desiccation probably caused a further orientation of water dipoles which promoted the formation of water stable aggregates. The formation of soil aggregates by wetting and drying cycles in a puddled soil has been shown by Peterson (1943). Woodburn (1944) found that wetting and drying resulted in the formation of water stable aggregate in the Houston clay, but not in the Memphis silt loam. Further, he showed that one cycle of wetting and drying was enough to produce water stable aggregates of 0.5 - 2.0 mm diameter, and a further succeding wetting and drying cycles reduced the amount of these aggregates. The proportion of 0.02 - 0.5 mm aggregates still increased up to 2 cycles of wetting and drying, and then decreased on further cycles.

White (1966; 1967) has suggested that the main agent for structure development in sub-soils is expansion and contraction due to alternate wetting and drying. In studying the aggregation of allophane soils, Kubota (1972) found that drying resulted in aggregation of some silt and clay particles. He, therefore, suggested that drying might be the main agent responsible for aggregate formation in these soils. Wetting and drying cycles were used by Coughlan and Fox (1977) to produce soil aggregates. They considered that aggregation was complete when the bulk density of dry aggregates did not change appreciably with further wetting and drying cycles.

Cracks which develop during drying have been suggested to constitute the initial faces of soil aggregates (White, 1966). As the thickness of water layer surrounding particles becomes reduced, individual sand, silt, and clay particles are brought close together. If interparticle water films are lost, a soil changes from semi plastic mass to a brittle material which can readily break down into aggregates. Baver *et al.* (1972) considered that the dehydration of a soil mass cannot be uniform, especially if the drying process is rapid. Consequently, unequal stresses and strains arise throughout the mass of the soil, and this, as suggested by White (1966), can result in aggregate formation.

Wetting of the shrunken soil produces swelling which closes the cracks. This crack closure associated with swelling can cause stresses to develop in the boundary zones between soil layers of different water content (White, 1966). This process can lead to the initiation of soil aggregate formation.

It is common knowledge that wetting a dry clod can result in the breakdown of the clod into finer soil aggregates. There are two processes which govern the break-down of these clods, these are:

(1) unequal swelling due to rapid intake of water producing fracture and fragmentation, and (2) compression of entrapped air due to water entry into the soil pores.

The breakdown of clods due to swelling is significant only when the soil contains clay minerals which exhibit appreciable swelling behaviour. Emerson (1954) and Emerson and Grundy (1954) found that the breakdown on wetting of clods from some British soils is due to the dispersion of the clay in the clods. For these soils, in which the clays are effectively calcium saturated, the breakdown resulting from swelling is negligible. Dettmann (1958) wetted pure clays, and concluded that entrapped air is neither necessary nor important factor in slaking of dry clods, and that slaking is always associated with rapid intercrystalline swelling of the clay. If swelling was suppressed or occurred slowly through, for example wetting from the vapour phase, slaking did not occur. Slow swelling gives time for readjustment of the internal geometry of the clays. As a result, slow swelling produces dislocation, but not complete disruption.

The extent to which a clod will breakdown on wetting is determined by the balance of the driving forces for the entry of water and cohesive forces that hold particles together (Winterkorn, 1942). As water moves into the soil, the affinity of the soil surfaces for water increases. If it exceeds the cohesive forces, soil aggregates lose their cohesion, and cementing bonds are destroyed. A mathematical representation for this condition has been given by Henin (1938). It is

$$rC + C_1 < 2A \qquad (2.3)$$

where r is the largest capillary in the soil, C is the apparent cohesion of the soil, C_1 is the cohesion of water, and A is the affinity of the soil for water.

Quirk (1950) noticed that soil aggregates with diameter of 2 - 5 mm did not breakdown into units smaller than 0.25 mm appreciably until the matric potential of the soil water at the time of wetting exceeded the potential of -5 MPa. The effect of water content at time of wetting on aggregate disruption has been received considerable attention (Cernuda, Smith and Vicente-Chandler, 1954; Panabokke and Quirk, 1957). It has been found that there is a certain water content at which soil aggregates do not slake appreciably upon wetting. The result of Panabokke and Quirk (1957) showed that for the Urrbrae fine sandy loam the minimum slaking occurred when the initial matric water potential of the aggregates was about -10 kPa.

Aggregate water content at time of wetting influences the development of internal slaking through its effect on the amount of air available for trapping, and through its effect on the rate of water entry. It has been found that slaking of soil aggregates increases with increasing rate of wetting (Emerson and Grundy, 1954).

Telfair, Garner, and Miars (1957) found that wetting and drying a soil produced a platy structure with cracks usually running horizontally. White (1966) proposed a classification for sub-soil structures formed mainly by wetting and drying cycles as follows: (1) faces of blocky peds, (2) faces of prisms, (3) faces of columns, (4) faces of parallelepiped, (5) faces of granules, and (6) faces of peds. Van de Graff (1978) studied the aggregation process based on the concept of externally induced oriented stress regime caused by uneven shrinking and swelling. He found that the stresses developed during rapid drying produced smaller peds than those developed during slow drying. Low rate of wetting and drying produced smaller stresses giving better possibilities for stress relaxation. Consequently, with lower rates, there was less intensive cracking, and hence the aggregates produced were larger.

The breakdown of dry clods when they are wetted is well known. How wetting and drying cycles affect aggregate water stability, however, is still debatable. Willis (1955) studied the effect of wetting and drying on the water stability of soil aggregates treated with HPAN (a sodium salt of hydrolyzed polyacrilolnitrite) and SC-50 (a water soluble sodium siliconate $CH_3Si(OH)_2ONa$). Using the wet sieving method he found that except for the Edina silty clay loam (untreated and SC-50 treated), untreated Ida silt loam, untreated Shelby loam, the cycles of wetting and drying decreased aggregate water stability, as shown by the percentage of aggregates larger than 0.25 mm diameter. For those above mentioned treatments, a single wetting and drying cycle increased aggregate stability, but further wetting and drying cycles decreased aggregate water stability. A decrease in aggregate water stability, as shown by the proportion of aggregate larger than 0.5 mm diameter obtained by the wet sieving method developed by Bryant *et al.* (1948), due to wetting and drying cycles has also been found by Soulides and Allison (1961) on the Codorus silt loam, Elliot silt loam, Chester sandy loam, and Fargo silty clay loam.

Rovira and Greacen (1957) and Tisdall, Crockroft and Uren (1978) used dispersion test to study the effect of wetting and drying cycles on aggregate water stability. Rovira and Greacen (1957) used disaggregation, which was defined as the ratio of % particles smaller than 50 µm obtained by the weak dispersion of Marshall (1956) to that of obtained by mechanical analysis, and Tisdall, Cockroft and Uren (1978) preferred the percentage of particles smaller than 20 µm obtained by Blackmore (1956) method, which was defined as % slaking, to show the effect of wetting and drying cycles on aggregate water stability. It was found in these two works that aggregate water stability decreased with wetting and drying cycles, as shown by the increase in disaggregation

(Rovira and Greacen, 1957), or by the increase in % slaking (Tisdall *et al.*, 1978).

Tisdall *et al.* (1978) explained the decrease in aggregate water stability of a soil subjected to wetting and drying cycles in terms of microorganism activity. They suggested that wetting and drying cycles restrict microbial activity, so that bonds destroyed during wetting and drying can not be replaced. To test this suggestion, they wetted and dried a sterilized soil and found that the decrease in aggregate water stability of sterilized soil was much greater than that of unsterilized soil.

Sillanpaa and Webber (1961) and Richardson (1976) found a contrary result to that mentioned above. Using wet sieving, Silanpaa and Webber (1961) found that wetting and drying up to 5 cycles increased the mean weight diameter of aggregates with the initial size of 2.0 - 3.0 mm and of the crushed aggregates (< 0.25 mm diameter), but did not influence the MWD of original aggregates with the initial diameter of < 0.25 mm. The clay content of these aggregates was 36.3%, 35.6% and 29.3% for 2.0 - 3.0 mm original aggregates, crushed aggregates, and < 0.25 mm original aggregates respectively.

Richardson (1976) employed a dispersion test (Middleton, 1930) to study the effect of artificial weathering on the structural stability of the Holland fine sandy loam of Lincolnshire, England (18% clay and 15% silt). The result was given in terms of "dispersion ratio" which was calculated from the amount of silt and clay obtained as a percentage of the total silt and clay in a sample of original untreated soil which had been completely dispersed with a 10% calgon solution and destruction of the organic matter with hydrogen peroxide. He found that after 3 cycles of wetting and drying the water stability of aggregates of the cycled soil was higher than that of non-cycled soil. To study the micro structure at the surface of aggregates he took scanning electron micrographs. The most striking difference between treatments was that the finer particles in the cycled soil had been oriented parallel to each other to much greater degree than in non-cycled soil.

Hofman (1976) found that the instability of soil aggregates sieved immediately after sampling was higher than that obtained when the soil was first air dried and then rewetted to its original water content or to field capacity. He suggested that this was probably due to changes in the organisation of the soil constituents, such as a more stable orientation of the clay particles, variation in the distribution of organic matter, or/and modification of the physical structure of the organic matter, such as a change of surface area of this coloidal material as has been suggested by Nevo and Hagin (1966).

2.1.3 Freezing and thawing cycles

The formation of ice crystals and their subsequent melting in a soil caused by alternate freezing and thawing can assist the development of soil aggregates. Water expands on freezing by about 9% (volumetric), and results in the enlargement of soil pores with a consequent loosening effect upon the soil. During this process water migrates from around the clay particles to the growing ice crystals which creates local dehydration. The combination of ice crystal pressure and dehydration provides an initial condition for aggregate formation. Corte (1962) and others (e.g. Norrish and Rausell-Colom, 1962, Anderson and Hoekstra, 1965) have suggested that as water is drawn from suspension and frozen, aggregation occurs as a combination of the migration of particles in the front of ice-liquid interface, and the removal of interlamelar water from the clay.

The structure formed by freezing and thawing cycles depends on the soil type, rate of freezing and thawing, and the water content at the time of freezing (Baver *et al.*, 1972). Russell (1950) has concluded that freezing and thawing improves the structure of clay soils with high organic matter content, but adversely affects silty soils with low organic matter content. This is in consistent with Ceratzki (1956) who found that freezing coarse-textured soils produced a homogenous mass with no obvious difference in its microscopic structure. When fine grained soils were frozen, ice crystalized in layers within the soil materials, and resulted in the formation of the so-called "frost structure". Bisal and Nielsen (1964) observed that a clay soil was more finely aggregated after frost action, and was thus more susceptible to wind erosion. A clay loam was less erosive, and no change occurred in a sandy soil.

The aggregating effect of frost is related inversely to the rate of freezing (Harris *et al.*, 1966). Slow freezing results in the formation of large ice crystals and large stable aggregates. Rapid freezing causes the formation of many small ice crystals and smaller aggregates. Rowell and Dillon (1972) studied the effect of freezing on aggregation based on migration of clay particles. They found that a freezing rate of 10 mm per hour did not move flocculated clay, but moved dispersed clay up to 7 mm before it became trapped in the ice with released air. Further, they observed that freezing and thawing of clay suspension at > 10^{-2}M $CaCl_2$ produced aggregates in the form of flocs of about 1 mm diameter. At < 10^{-2}M $CaCl_2$, aggregates were produced in the form of flakes, often with curled edges becoming more blocky with decreasing concentration, and their size increased from about 0.1 mm to 1.0 mm diameter.

Aggregation may be improved if the soil at time of freezing is not too wet (Russell, 1950). When the soil is very wet, freezing and thawing even may destroy the previously existing aggregates. Benoit (1973) found that the formation of > 0.05 mm diameter water stable aggregates from an initially unaggregated soil was greater by a factor of 1.10 and 1.26 (for rapid and slow freezing) than that in the untreated soil when matric water potential at time of freezing was about -50kPa. When the water content at the time of freezing corresponded to the maximum water holding capacity, the proportions formed were only 0.92 and 1.10 (for rapid and slow freezing) of those in untreated soil.

In studying the effect of freezing and thawing cycles on aggregate stability of Haldiman clay, Logsdail and Webber (1959) found that the water stability of aggregates from a continuous corn plot is not influenced by freezing and thawing cycles. For this phenomenon, they suggested that the initial level of aggregation in this soil had attained a value which was not significantly affected by alternately freezing and thawing. This suggestion agrees with the finding of Slater and Hopp (1949) that soils of good quality (a high value of initial aggregate water stability) suffered a larger reduction in aggregate water stability than soils of poor quality.

Willis (1955) studied the effect of freezing and thawing cycles on aggregate water stability of soils treated with chemicals. Except for Edina silty clay loam and Lagonda clay loam treated with SC-50, aggregate water stability decreased with freezing and thawing cycles. For these two treated soils, aggregate water stability was increased by 1 cycle of freezing and thawing, but was decreased by further freezing and thawing cycles. An increase in MWD of crushed aggregates due to freezing and thawing cycles has been found by Sillanpaa and Webber (1961). For the natural aggregates, they found that freezing and thawing decreased the MWD of aggregates with initial diameter of 2 - 4 mm, but did not influence the MWD of aggregates with initial diameter of < 0.25 mm.

The importance of initial size of aggregates in determining the final effect of freezing and thawing has also been stressed by Hinman and Bisal (1968) and Benoit (1973). Benoit (1973) found that freezing and thawing of aggregates with initial diameter < 0.8 mm increased the proportion of water stable aggregates > 0.5 mm. When the initial diameter was > 1.2 mm, however, freezing and thawing cycles greatly reduced the proportion of water stable aggregates larger than 0.5 mm.

Richardson (1976) studied the effect of freezing and thawing cycles on aggregation of puddled fine sandy loam of Holland, Lincolnshire, England. He found that after only 3 cycles of freezing and thawing, aggregation reached a maximum value which was slightly greater than unpuddled soil. He, therefore, suggested that the structure of severely damaged fine sandy loam could be restored by alternate freezing and thawing.

2.1.4 Tillage

During tillage soil structure is modified by the implement through shearing, compressing, and inverting the furrow slice. Although tillage is not capable of forming water stable aggregates (Rogowski and Kirkham, 1962), it at least, initiates the formation of soil aggregates, so that stabilization by other mechanisms can proceed. This initiation might result from the separation of aggregates which already exist in the soil, or/and which have been formed by other processes, such as wetting and drying, freezing and thawing, and even the mechanical action of soil flora and fauna. Tillage can have a high efficiency if it makes use the existing planes of weakness, such as cracks, in the soil.

The size distribution of aggregates produced by tillage is influenced by the properties of the soil, the condition of the soil at the time of tillage, and the performance of the tillage implement. It is well known that the effect of tillage on soil structure is a function of soil water content at time of tillage (Russell, 1938; Vershinin, 1959). When tillage is performed in a very wet soil, it cannot produce a good tilth, and may even destroy the previously existing aggregates. Likewise when tillage is performed in a dry soil, excessively large clods are produced instead of small stable aggregates.

The effect of water content at time of tillage on soil structure produced has been extensively studied (Lyles and Woodruff, 1962; Bushan and Ghildyal, 1972; Ojeniyi and Dexter, 1979a). In general, it has been found that the optimum water content for tillage is around the plastic limit (Ojeniyi and Dexter, 1979a).

The optimum water content for tillage is influenced by the pressure exerted by the tillage implements, and the speed of tillage (Vershinin, 1959). The higher the pressure exerted by tillage implement, the lower is the optimum water content for tillage. This is in agreement with Russell's (1938) suggestion that the more intensive the tillage, the lower is the optimum water content at which tillage can be performed. Swanson, Hanna and De Roo (1955) found that excessive tillage (at high water content) broke down the aggregates larger than 2 mm, and decreased aggregate water stability. Rovira and Greacen (1957) simulated tillage in the laboratory, and found that disaggregation increased with increasing tillage intensity and water content at time of tillage.

The influence of implement shape on soil structure produced by tillage has been studied by Gill and McCreery (1960) and others (Bushan and Ghildyal, 1971; 1972; Ojeniyi, 1978). It has been found that a mouldboard plough produces larger clods than a disc plough (Gill and McCreery, 1960) and than a cultivator (Bushan and Ghildyal, 1971). For Urrbrae fine sandy loam, Ojeniyi (1978) has shown that a mouldboard plough produces a smaller proportion of small aggregates than a scarifier or rotary cultivator. This difference may in part be a consequence of differences in the radii of curvature of the implements used. It has been found that the MWD of clods produced by tillage increases with increasing the radius of curvature of the implements (Bushan and Ghildyal, 1971; 1972).

2.2 Strength of the cohesive soil

Soil strength is defined as the ability or capacity of a soil to resist or endure an applied stress (Gill and Vanden Berg, 1967). In addition, since strength is not evident without strain, soil strength might be defined as the capacity of a soil to withstand deformation or strain. Soil strength may be described in terms of the parameters of stress-strain equations, or be evaluating the parameters in yield conditions.

For ductile materials, yield can be defined as the stress, S, at which permanent deformation first occurs. In the case of perfectly plastic materials, the yield point does not vary and the yield surface is fixed with plastic strain occurring only if S is on this surface and stays on it. Salencon (1977) expressed the yield criterion for these materials by

$$f\ (S) = 0 \tag{2.4}$$

where f is a scalar function of the state of stress of the materials. Thus $f\ (S) < 0$ corresponds to the elastic range of materials, and $f\ (S) > 0$ corresponds to the appearance of irreversible deformations.

With work-hardening materials, the yield point varies as the permanent deformation continues, so discrimination between the original and current yield surface must be made. Additional plastic strain appears only if S is situated on the yield surface and moves outwards. If the work-hardening effect (E) is taken into account, equation (2.4) now becomes

$$f\ (S,E) = 0 \qquad (2.5)$$

A pictorial representation of yield in ductice materials is given in Figure 2.2.

In brittle (as distinct from plastic) materials, failure occurs as or just after the yield stress, S, is reached. In these materials, only a very little plastic behaviour is exhibited.

In nature, soils can be found as near-liquid materials, ductile materials, or brittle materials. The application of the term "yield", therefore, is very complex and often leads to confusion and misunderstanding. Because of this, Yong and Warkentin (1975) suggested that the term yield and failure could not be applied indiscriminately to soils.

In the past, especially in the field of civil engineering, research in soil mechanics has been centered on the shear strength of a soil. Consequently, failure is usually defined as shear failure. Newmark (1960) defined failure in a cohesive soil as the condition at the beginning of the loss of shearing resistance or at a relatively advanced state in the loss of shearing resistance. It is now realized that shear strength is not the only important strength property of soil. Kezdi (1979) has pointed out the importance of tensile strength in many problems of earth statics associated with a cohesive soil. From the agriculture viewpoint, Bateman *et al.* (1965) recognised that in tillage, soil fails in shear, compression, tension, and abrasion. Barley and Greacen (1967) suggested 3 types of failure produced by plants, namely (1) tensile failure, (2) shear without compression, and (3) shear with compression.

The intent of this review is to discuss the natural factors which contribute to the development of, and/or which influence the strength of

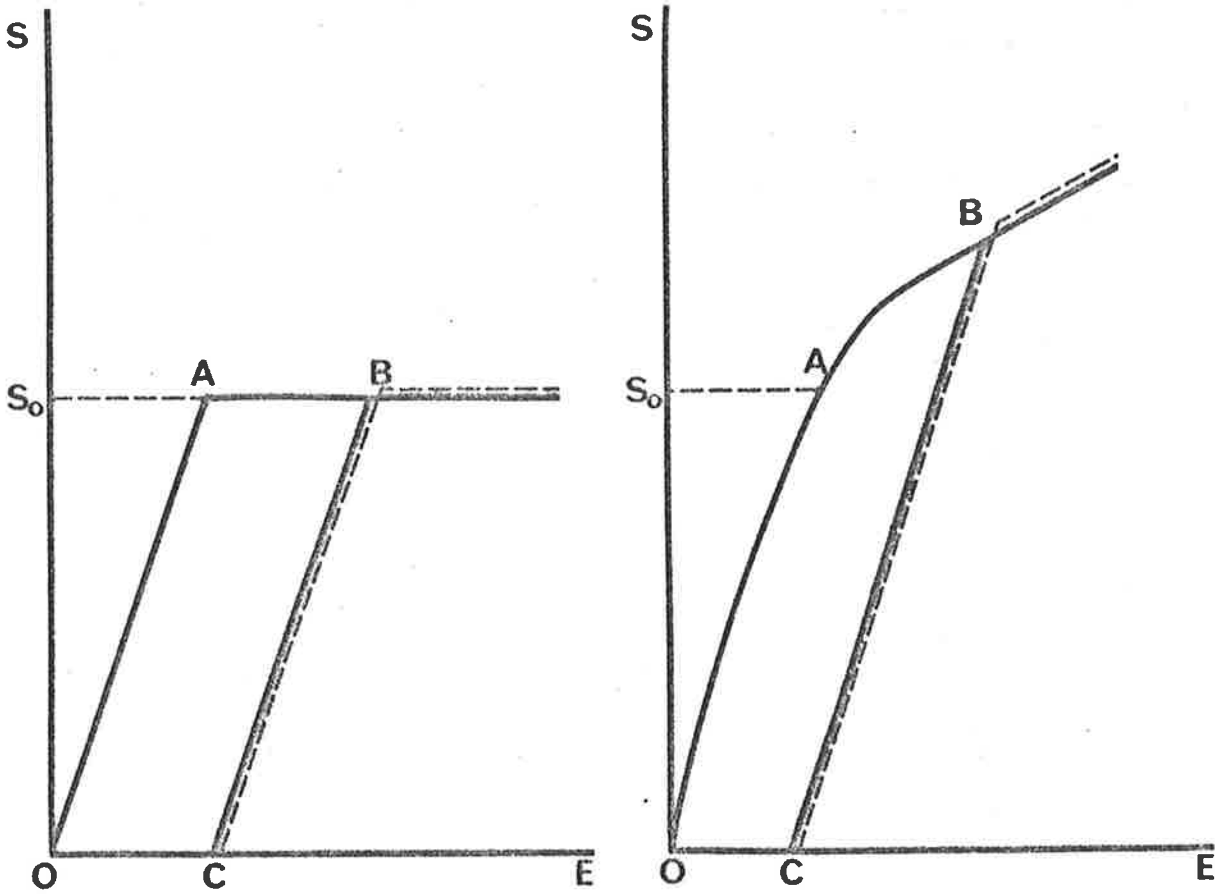


Fig. 2.2. Pictorial representation of yield in
(a) perfectly plastic material,
(b) work-hardening materials.

O - A = elastic region (reversible deformation).
A = yield point, when $S > S_o$, irreversible deformation occurs.

a soil. The mathematical treatment of soil strength, therefore, is not treated in detail. In addition, factors which are considered to be non-natural factors, such as rate of strain, rate and time of loading etc., are not discussed in this review. The influence of these factors on soil strength can be found elsewhere in soil mechanics text books (e.g. Lambe and Whitman, 1969; Yong and Warkentin, 1975; Mitchell, 1976).

2.2.1 Shear strength

Failure by shear is identified by the occurrence of failure plane(s) in the direction of greater shear stress and always between this direction and the direction of the compressive stress (Yong and Warkentin, 1975). This type of failure can be seen perfectly in brittle materials. Since a soil may also have a brittle property, this type of failure can also occur in soil, especially when the soil is dry. When soil water content is high enough, the soil may not fracture, but the diameter of the specimen under test gradually increases with increasing applied stress. The increase in diameter is a permanent deformation, and the level of stress causing this deformation, therefore, can be referred to as a measure of shear strength.

The first theory of shear failure was developed by Coulomb in 1776, and is known as "the maximum shear theory" (Yong and Warkentin, 1975). In this theory, it is suggested that failure occurs when the maximum shear stress reaches some critical value. The maximum shear stress theory was extended by Navier, and then by Mohr who considered that failure by both yielding and fracture can be expressed as a functional relationship between the normal and shear stresses on the failure plane:

$$\tau_f = f(\sigma_N) \qquad (2.6)$$

where τ_f is the shear stress at failure along the failure plane, and σ_N is the normal stress on the failure plane.

For a cohesive soil, equation (2.6) is usually written

$$\tau_f = C + \sigma_N \tan \emptyset \qquad (2.7)$$

Here C is the cohesion (shear cohesion), and Ø is the angle of internal friction.

The simplest way to represent equation (2.7) is to construct Mohr's circle, and the method is now known as the "Mohr - Coulomb" theory. Along the abscissa lie the principal stresses, σ_1, σ_2, σ_3, and along the ordinate lies the shearing stress.

To understand the principal stresses, it is necessary to recognize the principal stress planes. At any point in a stressed material, there exist three orthogonal planes on which the shear stresses are zero. These planes are the principal stress planes, and the normal stresses acting on these planes are called the principal stresses. The largest stress is called the major principal stress, σ_1, the smallest stress is called the minor principal stress, σ_3, and the intermediate stress is called the intermediate principal stress, σ_2. The maximum shear stress, τ_{max} is independent of σ_2 and is given by

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} \qquad (2.8)$$

The shear strength of soil has been found to be not significantly affected by σ_2.

Mohr's failure envelope is usually drawn as a straight line as shown in Figure 2.3a. Although this is usually a close approximation to the experimentally observed behaviour, the actual Mohr failure envelope is often slightly curved (Figure 2.3b).

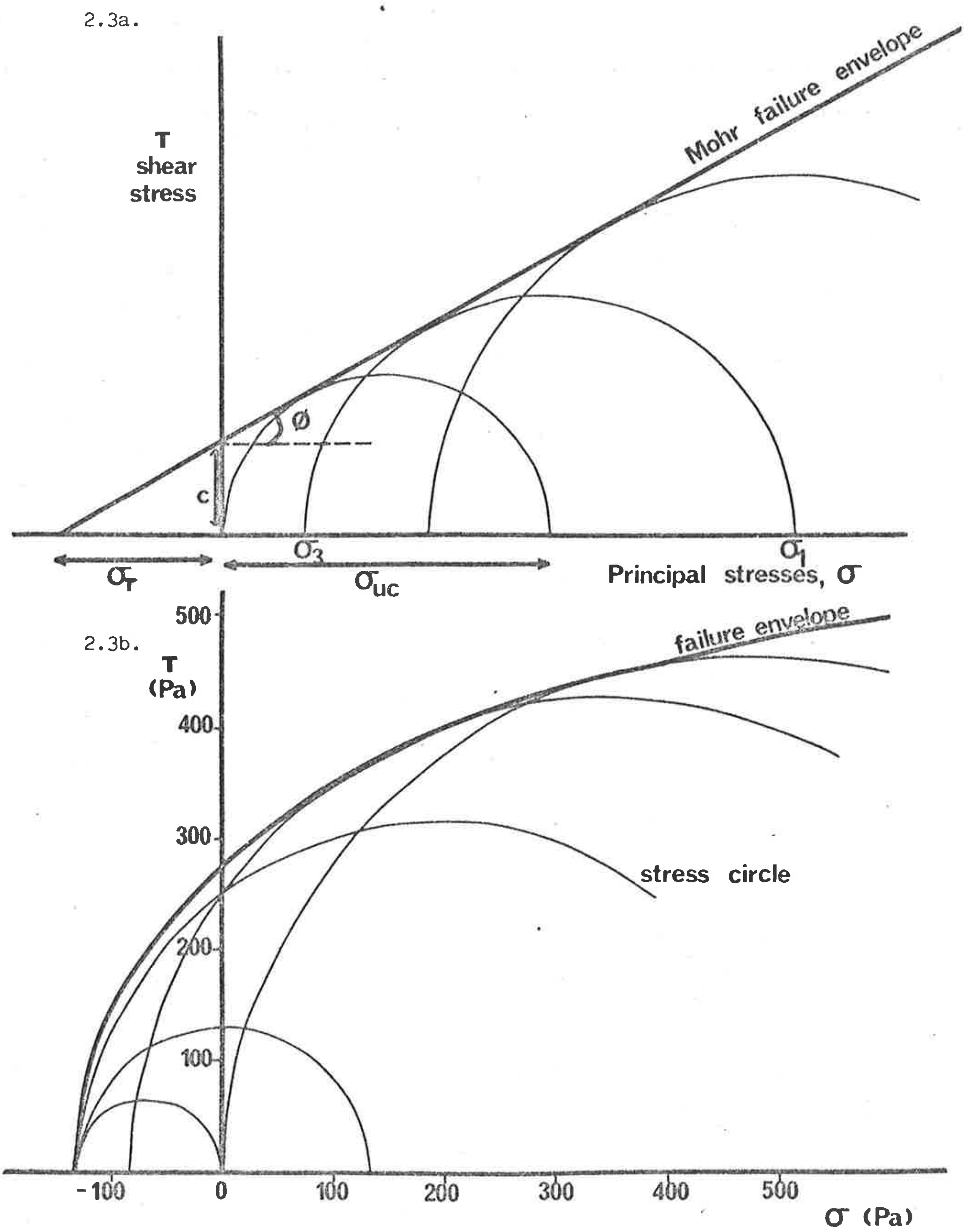


Fig. 2.3. Representation of shear strength of a cohesive soil in Mohr's Circle.

a. a common (simplified) method.
b. actual Mohr's failure envelope obtained from the Parafield Loam (Farrell *et al.*, 1967).

Besides the shear strength, the envelope of the Mohr's circles shown in Figure 2.3a, b also shows the tensile strength, σ_T. Along the abscissa, stress to the left represents the tension (σ_T), and to the right represents compression. The relationship between unconfined compressive strength, σ_{uc} (measured when $\sigma_2 = \sigma_3 = 0$), tensile strength σ_T, and shear strength parameters can be expressed in the following equations (Vomocil and Chancellor, 1967)

$$\sigma_{uc} = \frac{2\sigma_T \sin \phi}{1 - \sin \phi} \qquad (2.9a)$$

$$C = \sigma_T \tan \phi \qquad (2.9b)$$

However, these are only valid for the idealized and unrealistic case of flawless soil shown in Figure 2.3a. Due to cracks within the soil, the ratio of σ_{uc}/σ_T varies, with the Mohr's envelope a curve as shown in Figure 2.3b. Vomocil and Chancellor (1967) reported values of σ_{uc}/σ_T ranging from 3 - 6 for silt loam, and from 2 - 4 for a silty clay. With the Parafield loam of 1.7 g/cm^3 density and water content range of 2% - 12%, Farrell, Greacen and Larson, (1967) obtained values from 8 - 10. When the density was 1.3 g/cm^3 and water contents of 6 - 28% they obtained values from 6 - 10 (Farrell, Larson and Greacen, 1967). The definition of unconfined compressive strength, σ_{uc}, and tensile strength, σ_T, and a further discussion of these strength properties is given in sections 2.2.2 and 2.2.3 respectively.

One confusing factor in understanding the Mohr-Coulomb theory is that C and Ø are so firmly entrenched that they are often referred to as real physical properties of the soil (Gill and Vanden Berg, 1967). In reality, they are only parameters of assumed yield equations. In addition, equation (2.7) represents shear failure at one single point, whereas the actual failure is on a plane and can also be represented on a failure surface. The failure surface corresponding to the Mohr-Coulomb condition of failure is

$$[(\sigma_1 - \sigma_2)^2 - \{2 C \cos \emptyset + (\sigma_1 + \sigma_2) \sin \emptyset\}^2] \times$$
$$[(\sigma_2 - \sigma_3)^2 - \{2 C \cos \emptyset + (\sigma_2 + \sigma_3) \sin \emptyset\}^2] \times \qquad (2.10)$$
$$[(\sigma_3 - \sigma_1)^2 - \{2 C \cos \emptyset + (\sigma_3 + \sigma_1) \sin \emptyset\}^2] = 0$$

This can be shown on a three-dimensional diagram with σ_1, σ_2 and σ_3 as axes. The failure surface is a pyramid with the space diagogonal major normal stress (σ_1) = intermediate normal stress (σ_2) = minor normal stress (σ_3). The cross-section is an irregular hexagon with nonparallel sides of equal length as shown in Figure 2.4.

Mohr's theory specifies a functional relationship between the effective or statistically macroscopic interparticle stresses rather than the externally applied stress. This theory, therefore, cannot be readily applied to unsaturated soil. For this condition, Bishop (1959) used the effective normal stress (σ_N') instead of the total normal stress. Thus

$$\tau_f = C' + \sigma_N' \tan \emptyset' \qquad (2.11)$$

where $\sigma_N' = \sigma_N - \mu a + \chi (\mu a - \mu w)$

Here μa denotes the pressure in the gas and vapour phase, and μw denotes pressure in pore water. C' and Ø' are the shear cohesion and angle of internal friction in terms of effective stress. The value of χ varies from 0 for air-filled pore space to 1 for water-filled pore space.

The problem is now how to measure χ. For a fixed particle arrangement χ is assumed to depend primarily on the degree of saturation. In a real field condition, however, the problems become very complex, and is very difficult to obtain a single value of χ (Aitchison, 1965).

For soils which are always measured at known matric water potential, Ψ_m, and for which air pressure is always constant and equal to atmospheric pressure as in this work, equation (2.11) can be written

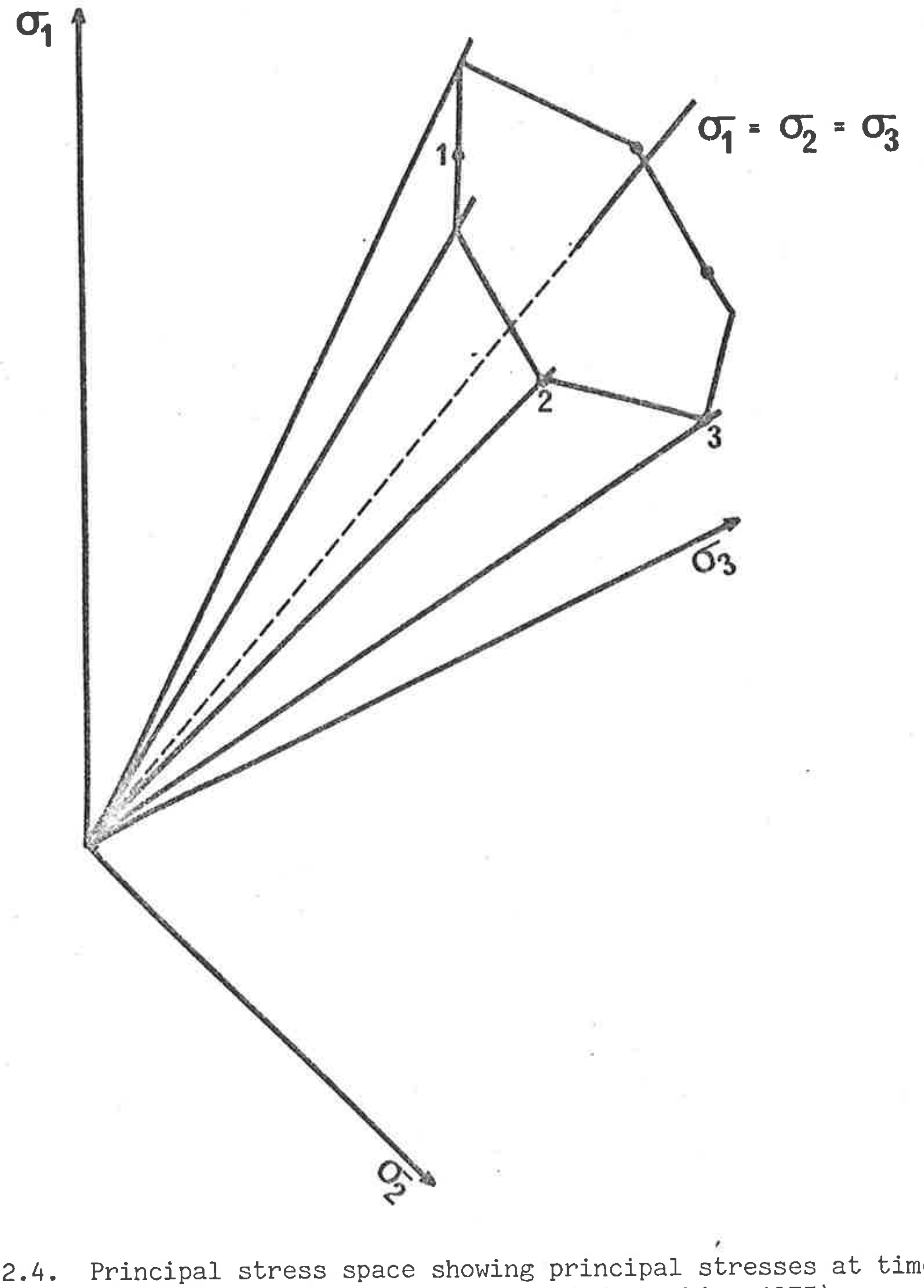


Fig. 2.4. Principal stress space showing principal stresses at time of failure (redrawn from Yong and Warkenhin, 1975), point 1, 2, and 3 etc. represent a combination of σ_1, σ_2 and σ_3 producing yield in a material in a particular stressing situation. When these points are joined will form a common octahedral plane which is called the yield surface.

$$\tau_f = C' + (\sigma_N - \chi\Psi_m) \tan \emptyset' \qquad (2.12)$$

As soil dries from saturation, χ decreases from 1 to 0, and Ψ_m decreases from 0 to $-\infty$. Hence $(-\chi\Psi_m)$ is positive and goes to a maximum at potential somewhere around Ψ_m = -10 kPa.

Williams and Shaykewich (1970) related the value of χ to the matric water potential. They found that at a matric water potential of about -100 kPa, χ was about 0.4 and 0.1 for the Gretna clay and the Wellwood loam respectively. When the matric water potential was about -1 MPa, the corresponding values of χ were 0.1 and 0.0.

Lambe (1960) interpreted shear strength in terms of interparticle forces. He suggested that there were several forces acting between particles, namely (1) F_m: force where contact is mineral - mineral; (2) F_a: force where contact is air - mineral; (3) F_w: force where contact is water - mineral or water - water; (r) R': electrical repulsion between particles; and (5) A': electrical attraction between particles. With these forces, he proposed an equation

$$\sigma_N = \sigma' A_m + P_a A_a + \mu A_w + R - A \qquad (2.13)$$

where σ' is the effective stress between minerals derived from and associated with F_m; A_m is the unit contact area for mineral - mineral; P_a and A_a are the unit pressure and unit area directly associated with F_a; μ and A_w are the pore water pressure and unit area directly associated with F_w; R and A represent unit electrical forces of repulsion and attraction respectively.

It is, however, very difficult, if not impossible to measure all the components listed above. To overcome this difficulty, Yong and Warkentin (1975) simplified equation (2.13) into

$$\sigma_N = \sigma' + \mu + (R - A) \qquad (2.14)$$

for saturated soil.

Equation (2.7) and (2.11) show that the factors responsible for the shear strength of a cohesive soil are the frictional resistance and the shear cohesion. Lambe (1960) divided the shear strength component into three basic components. These are, (1) cohesion, (2) dilatant, and (3) friction. However, it is not possible to adequately separate and study the contributions of these components.

The friction angle used in equations (2.7) and (2.11) which is often referred to as the physical component of shear strength arises primarily from the resistance to relative movement of sliding of one particle on another, and to interlocking between particles. Rosenqvist (1959) divided the interlocking phenomemon into (1) microscopic interlocking resulting from surface roughness of particles which results in small movement of particles normal to the failure plane, and (2) macroscopic interlocking of particles requiring appreciable movement of particles normal to the failure plane, and hence resulting in an increase in volume prior to failure. According to Rowe (1962) the frictional resistance arises from sliding of grains in contact, resistance to volume change, grain rearrangement, and grain crushing.

The value of frictional resistance can be described by using the angle of internal friction, or by using the coefficient of friction (f) which is equal to tan Ø. in this thesis, the first method is used.

It has been found that frictional resistance can exist between granular materials, such as quartz, feldspar, and calcite, as well as in between sheet minerals, such as mica. Some factors that have been found to influence the magnitude of the frictional resistance are particle size, water content, surface roughness, and packing of the particles.

The effect of particle size on friction angle has been studied by Rowe (1962) who showed that the angle of internal friction decreased with increasing particle size. Coarse silt had a friction angle of 30°, whereas fine, medium, and coarse sand had a friction angle of 28°, 25°, and 22° respectively. It seems that the larger particles are able to roll more easily than the smaller particles, perhaps as a result of their centre of gravity being further away from the plane of shear (Lambe and Whitman, 1969). Consequently, the friction angle will be smaller as the size of particles are larger. When these materials are mixed with clay, however, the opposite effect has been observed. Kenney (1967) found that both in clay - quartz mixture and in natural soils the friction angle decreased with increasing clay content. Further, he found that with the same clay mineral content, the friction angle of soil containing hydrosmica was greater than that containing montmorillonite. The friction angle of Selnes soil containing about 50% hydrosmica was about 30°. For Vayont soil containing about 50% montorillonite, the friction angle was only about 10°.

The effect of water content on the friction angle of grain mineral differs from that of sheet minerals (Horn and Deere, 1962). Water acts as an antilubricant when it is applied to the surface of grain minerals, and as a lubricant when it is applied to the surface of sheet minerals. Horn and Deere (1962) found that oven-dried quartz from Wisconsin had a friction angle of about 9°. When this quartz was oven dried and then air equilibrated, the friction angle was about the same as it was in the oven dried condition. When it was saturated, however, the friction angle increased to about 15°. For sheet minerals, Horn and Deere (1962) showed that the friction angle of muscovite was about 22°, 18°, and 12° for oven-dried, oven-dried air equilibrated, and saturated conditions respectively. Panwar and Siemens (1972) measured the friction angle of

Drummer silty clay loam with clay content of 31%, plastic limit of 31% and liquid limit of 58%, and found that the friction angle decreased with increasing water content from W = 16% to W = 25%, above 25% a further increase in water content did not influence the friction angle.

It has been found that friction angle increases with increasing surface roughness (Horn and Deere, 1962). Surface roughness had more influence on the friction angle of quartz under oven dried or oven-dried air equilibrated conditions than it had under saturated condition. Based on this result, Horn and Deere (1962) suggested that the anti-lubricating action of water diminished rapidly as the surface becomes rougher. A similar result has been found by Bromwell (1966).

The influence of packing density on the friction angle can be explained from interlocking, and is hence a dilation phenomenon. As discussed previously, the frictional resistance of a soil is made up of the frictional resistance of grains on contact, particle rearrangement, grain crushing, and dilation. At high porosity (thus high void ratio), the frictional resistance arises from sliding between grains only. As the void ratio decreases, in addition to the work required to move particles relative to one another, frictional resistance also arises from the work required for particle rearrangement and/or dilation. The void ratio at which failure occurs at a constant volume, thus at which no work is required to produce dilatation is called the "critical void ratio". This critical void ratio is obtained at large strains and corresponds to the "residual" rather than the "peak" soil shear strength. Thus angles of internal friction angle measured from plots of residual strength against normal stress are independent of initial soil packing density or void ratio. It has been found that for a packing of medium-fine sand with maximum unloaded porosity of 46%, this critical void ratio corresponds to a porosity of about 42% (Rowe, 1962).

The more dense is the soil, the greater is the expansion which tends to take place during shear. Thus more energy (hence more force and a higher friction angle) must be expended to shear the soil. This is in good agreement with the result of Panwar and Siemens (1972) which showed that at 20% water content the friction angle at (peak) failure of the Drummer silty clay was about 25^o, 35^o, and 40^o for bulk densities of 1.2; 1.3 and 1.4 g/cc respectively.

Rowe (1962) found that the friction angle of medium sand increased with decreasing void ratio. At a void ratio of 42% the friction angle was about 30^o, and when the void ratio of this packing was 38% and 34%, the friction angle was 34^o and 40^o respectively.

Frictional resistance may some times be considered as a physico-chemical phenomenon (Yong and Warkentin, 1975). Because particle surfaces are not absolutely smooth, when two particles are brought into contact each other under stress, the contact point will deform elastically or plastically to an amount sufficient to sustain the applied effective stress. The close proximity of contacting areas results in adhesion due to electrical forces of attraction. The adhesive forces contribute to shear resistence, and must be overcome if sliding between contracting particles is to occur.

Shear cohesion may be interpreted as the shear strength at zero normal stress. Again, it must be remembered that the shear cohesion value in equations (2.7) and (2.11) is only an analytical parameter. This must not be confused with the property of true cohesion, or inter-particle cohesion. As discussed previously, the analytical parameter of shear cohesion is obtained from laboratory tests coupled with application of a failure or strength theory. Cohesion as a property of a soil is considered further when discussing tensile strength in section 2.2.3.

As discussed previously, the shear strength of a cohesive soil is made up of the frictional resistance and shear cohesion. Any factor influencing these parameters, therefore, will influence the shear strength of the soil. The influence of soil water content on shear strength has been investigated by many workers (Greacen, 1960; Towner, 1961; 1974; McCormack and Wilding, 1979). Greacen (1960) found that with the same normal stress, the shear strength of saturated soil was lower than that of unsaturated soil. Towner (1961) suggested that internal soil water potential is equivalent to an external forces of the opposite sign. In a later study with 17 ADAS standard texture soils, Towner (1974) found that shear strength increased linearly with increasing water content. Using the Canfield (Aquic Fraguidalfs: fine loamy, mixed, mesic) and Geeburg (Aquic Hapludalfs: fine, illitic, mesic) soils with water content range of 15% - 30%, McCormack and Wilding (1979) described the decrease in the shear strength with increasing water content with a curvilinier relationship.

Shear strength increased with increasing plastic limit and plasticity index (Hampton, Yoder and Burr, 1962). Towner (1974) related shear strength to soil texture, and found that the shear strength of sandy loam soil was much lower than that of loam or clay soil. McCormack and Wilding (1979) showed that shear strength is positively correlated with coarse clay (1 - 2 μm), and negatively correlated with fine clay (< 0.08 μm) content. Further, they showed that shear strength was positively correlated to the total clay content.

It can be expected from Lambe's (1960) theory (equation 2.13) that soils with the same amount clay content may have different shear strengths. The shear strength of sodium montmorillonite is greater than that of calcium montmorillonite (Warkentin and Yong, 1962). Sodium montmorillonite is a highly swelling clay, thus it has a high interparticle repulsion.

According to equation (2.13) and (2.14) this will result in a high normal stress provided that expansion is prevented. Calcium montmorillonite, on the other hand, swells by a much smaller amount. Consequently the repulsion forces, and hence the normal stress is smaller.

A decrease in shear strength with decreasing interparticle repulsion can be explained by a model in which strength arises from the force required to readjust particles to form a failure plane (Warkentin and Yong, 1962). This readjustment is restricted by interparticle repulsion. Any decrease in interparticle repulsion, therefore, allows an easier particle readjustment, and hence, can result in a decrease in shear strength.

Warkentin and Yong (1962) have shown that the shear strengths of sodium and calcium montmorillonite decrease with increasing void ratio. McCormack and Wilding (1979) used bulk density instead of void ratio, and found that shear strength decreased with decreasing bulk density.

All present measurements of shear strength attempt to evaluate the two parameters C and Ø. Kept in mind, however, these are parameters of the mathematical representing of shear strength only. Physically, these two parameters are not separate or unique entities and so are not true physical properties. Until a different model is proposed, the measurement of shear strength will centre around evaluating shear cohesion and frictional resistance (Gill and Vanden Berg, 1967).

The oldest and simplest device to measure shear strength is that called the "direct shear apparatus". It was used by Coulomb in 1776 (Lambe and Whitman, 1969), and is still widely used. Several types of direct shear apparatus have been developed. These include that used for *in situ* measurement, such as "torsional shear box" described by Gollis-George and Lloyd (1978) to measure shear strengths of seed-beds.

In all direct shear apparatus, the normal and tangential (shear) forces are measured as well as the relative movement of the apparatus with respect to the soil. The normal and shear forces divided by the appropriate failure area gives the required stresses. Movement is generally expressed in term of strain. By plotting the shear stress against the strain, the shear strength (the shear stress at failure) can be determined. When there is a peak value in this relationship, failure is assumed to occur at this value, and when there is no peak value, failure is assumed to occur when the curve attains its limiting maximum (plateau) level. The shear strength parameters C and Ø can be found from a series of shear measurements at different levels of normal stress for a given soil condition. The shear stress at failure τ_f is plotted against the associated normal stress, σ_n. The slope of this curve represents the coefficient of internal friction, tan Ø, and the value of shear cohesion, C, can be found by extrapolating the curve to zero normal stress (equation 2.7).

Another common device to measure shear strength is the "triaxial cell". The name of triaxial device indicates that the stresses can be controlled along three axis. In reality, however, this is not the case, because most tests are done with the two lateral (intermediate and minor) principal stresses the same ($\sigma_2 = \sigma_3$). An excellent discussion on the measurement of soil strength with the triaxial cell has been published by Bishop and Henkel (1967). In this test, a cylindrical soil specimen is first subjected to confining pressure, σ_c, which equally stresses all surfaces of the specimen. Then the axial stress is increased, $\Delta\sigma_a$, until the specimen fails. As discussed previously, failure is judged to have occurred either when clear fracture is evident, or when the diameter of the specimen increases. Since there are no shearing stresses on the sides of the cylindrical specimen, the axial stress, $\sigma_c + \Delta\sigma_a$, is the major principal stress (σ_1), and the confining stress, σ_c, the minor (and intermediate) principal stress (σ_3). To obtain the strength parameters, C and Ø, a series of tests with different confining pressures are done. The resulting principal stresses are plotted on the absisca of the Mohr diagram, and circles with radii $R = \frac{(\sigma_1 - \sigma_3)}{2}$ are drawn. The coefficient of friction, tan Ø, is obtained by drawing tangent or envelope of these circles, and the shear cohesion value, C, can be obtained either by extrapolating this line to the zero normal stress, or from (Yong and Warkentin, 1975)

$$R = \frac{\sigma_1 - \sigma_3}{2} = C \cos \emptyset + \frac{(\sigma_1 + \sigma_3)}{2} \sin \emptyset \qquad (2.15)$$

The device called the "drop cone penetrometer" which in the past has been widely used by Swedish geotechnicians (Hansbo, 1957), is now again received much attention (Towner, 1973; Campbell, 1975). A commercial drop cone penetremeter, which consists of a penetrometer of $30^{o} \pm 1^{o}$ cone angle and 35 mm length with the mass of 80.0 g, has been built by the Laboratorie central des Ponts et Chauses, Paris (Campbell, 1975; 1976).

To measure shear strength, first the cone is adjusted to just touch the surface of the specimen. It is then released, and its penetration depth is measured after it has come to rest. Hansbo (1957) has given a relationship between the depth of penetration, h (mm), and the undrained shear strength, τ_u (N/m^2), as

$$\tau_u = k \frac{M}{h^2} \qquad (2.16)$$

where M (g) is the weight of penetrometer and shaft, and k is an adjustable parameter.

Towner (1973) has shown that the value of k is influenced by soil type, especially the texture of the soil. A clay soil has value of

$k = 7.9 \times 10^3$, and a clay loam, silty clay laom, silt loam, sandy loam, loamy fine sand soils ahve k values of 5.4×10^3, 7.4×10^3, 1.0×10^4, 6.9×10^3, 1.6×10^4, and 1.2×10^4 respectively.

The drop cone penetrometer has the additional advantage that, besides shear strength, it can also be used to measure Atterberg limits as has been done by Sheerwood and Ryley (1970) and others (Campbell, 1975; 1976; Campbell, Stafford and Blackwell, 1980; Mullins and Fraser, 1980).

2.2.2 Compressive strength

Compression can be considered as the change in volume of a soil under applied stress. Failure by compression, therefore, might be defined as the state of stress at incipient volume change (Gill and Vanden Berg, 1967). The compressive strength discussed here must be differentiated from unconfined compressive strength or the compressive strength obtained from shear strength measurement which is discussed by Lambe and Whitman, 1969).

The unconfined compressive strength is obtained from shear strength measurement with $\sigma_2 = \sigma_3 = 0$. In this test the unconfined compressive strength, σ_{uc}, is equal to the major principal stress at failure (Vomocil and Chancellor, 1967), and the shear cohesion can be calculated by Panwar and Siemens, 1972)

$$C = \sigma_{uc}/(2 \tan (\frac{\pi}{4} + \frac{\emptyset}{2})) \qquad (2.17)$$

Dexter and Tanner (1974) differentiated compression into consolidation and compaction. When deformation occurs with the expulsion of air compaction is said to occur, and when it occurs with the expulsion of water, consolidation is said to occur.

To describe the compressive strength defined above, it requires the stress and volume strain relationship. Bekker (1969) related plate sinkage, Z, to applied stress, S, with the equation

$$S = \left(\frac{k_c}{b} + k_\phi \right) Z^m \qquad (2.18)$$

where k_c is a cohesive modulus of deformation, k_ϕ is a frictional modulus, b is the smaller dimension of the loading area, and m is an adjustable parameter. The parameters k_c, k_ϕ and m have been used in studies of the sinkage and performance of wheels and tyres.

This equation, however, does not relate stress and volume changes directly. It has been widely assumed that the major principal stress is related to volume strain. This concept has been examined by Vanden Berg, Buchele and Malvern (1958) and Harris, Buchele and Malvern (1964). Neither was able to support or reject this concept. Despite the extensive work which have been done since Gill and Vanden Berg (1967) developed the idea of compressive strength discussed above (e.g. Vomocil and Chancellor, 1967; Bailey and Vanden Berg, 1968; Bailey, 1971; Aref, Chancellor and Nielsen, 1975), it seems that no satisfied stress - volume strain relationship has been developed. Consequently, simplifying assumptions are usually made.

Since compression can occur both with and without shear (Baver *et al.*, 1972), it is very difficult to differentiate between failure by shear and failure by compression. The failure by compression and by shear can be considered as two separate phenomenon only when the behaviour can be adequately described. Even so, shear and compressive failure must have a common basis, because in both cases, the same kinds of inter-particle bonds must be broken, and in both cases the same particles have to rearrange themselves.

It has been suggested that in a wet aggregated soil, compression occurs as a result of plastic deformation (Day and Holmgren, 1952; McMurdie and Day, 1958; Davis, Dexter and Tanner, 1973). Plastic deformation occurs when the applied stress overcomes the shear strength of the soil. In a dry aggregated soil, compression occurs as a result of aggregate rupture (Dexter, 1975; Kezdi, 1979), and it has been shown elsewhere that aggregate rupture occurs when the applied stress is capable of overcoming the tensile strength of the aggregates. Any factor which influences the shear and tensile strength of a dry aggregated soil, therefore, will influence its compressive strength. In addition, since compression occurs when there is a decrease in the volume of voids (Kezdi, 1979), packing of soil particles should also influence the compressive strength.

Because of the difficulty in defining the stress at which failure occurs, the compressive strength (as defined above) is usually not represented in terms of strength, but is represented as the resistance of the soil to compression. This can be shown by the changes in the volume of the soil, void ratio, bulk density, or packing density.

In discussing the work of some earlier workers, Harris (1971) showed that both the rate and total changes in bulk density for the Decatur silty clay loam, due to applied, stress was greater than that for the Loyd clay soil. Further, he showed that when clay, silty loam, and sandy loam soils were compacted at air dry equilibrium, there was no difference in the changes in bulk density. When the soils were compacted at a higher water content, however, the compressive strength of the clay soil was greater than that of the sandy loam soil. This was shown by the fact that the changes in bulk density of the clay soil were smaller than those of the sandy loam. At water content of 8%, the change in bulk density of the clay soil was 0.17 g/cm^3, whereas the change in bulk density of the sandy loam was 0.45 g/cm^3.

The difference in the compressive strength for different soil types may result from the difference in particle size distributions, clay content and clay type, cation type and cation concentration. Harris (1971) has suggested that the change in void ratio with applied stress is greater for a poorly graded soil than for a well graded soil. Well graded soil contains both coarse and fine grained particles. The number of particle contacts and the area of contact for any one particle, therfore, will be larger. Hence the resistance to shear induced motion in such a soil will be greater than that in a poorly graded soil.

The type of clay mineral determines the forces of attraction and repulsion and therefore also the soil structure. A soil containing sodium montmorillonite (which is a highly-swelling mineral) has a random structure. With kaolinite, on the other hand, the structure is flocculated. Here "flocculation" implies a close aggregation of particles without any specific orientation, whereas "random" implies an aggregation in random orientation but not in close contact (see Yong and Warkentin, 1975, p.83). Craford (1964) and Yong and Warkentin (1966) have shown that, at first, the change in void ratio with applied stress in a marine clay with an initial flocculated structure is very small, and lower than that in a remoulded clay with a random structure. When the structure has broken at a kind of "threshold" stress, the void ratio changes with further increases in applied stress are very large, and are greater than those in clays with random structure.

The attraction and repulsion forces in a soil are also influenced by the dominant type of cation present. The compressibility of kaolinite has been found to decrease according to the order of Li > Na > K > Ca > Ba, and for bentonite the order is Li > Na > Ca > K (Salas and Seratosa, 1953).

Chancellor and Schmidt (1962) evaluated the effect of initial bulk density on compressive strength in terms of k_c and $k_\emptyset$ in equation (2.18), and found that both for the Yolo loam and Greenfield sandy loam the value of k_c and $k_\emptyset$ increase with increasing initial bulk density. This shows that the greater is the initial bulk density, the greater is the compressive strength.

Compressive strength decreases with increasing water content down to a minimum value, and then increases with further increases in water content (Nichols, and Baver, 1930; Raghavan *et al.*, 1976). This minimum value usually exists within the plastic range. Harris (1971) has shown that with an initial bulk density of 1.4 g/cm^3 and an applied stress of about 138 kPa, the bulk density of sandy loam soil at 8% water content is about 1.9 g/cm^3. When the water content is 1.5%, the bulk density is only 1.5 g/cm^3. The decrease in compressive strength with increasing water content has also been found by Vomocil and Chancellor (1967) and Dexter and Tanner (1973a). Dexter and Tanner (1973a) found that the increase in packing density (defined as the volume of the soil occupied by solid particles) with applied uniaxial stress in a soil with 33% plastic limit and 54% liquid limit is greater at 25.3% water content than that at 16.5% or 6.7% water content.

A common assumption in the method used to measure compressive strength is that the major principal stress, σ_1, is the factor controlling the change in volume. The soil is usually confined in a suitable container, such as a cylindrical consolidometer cell, then uniaxial stress is applied to an exposed surface. The applied axial stress is considered to be the major principal stress. Unfortunately, the frictional characteristics of soil causes non-uniform stress distribution, and in a narrow compression cylinder arching may occur. To eliminate this effect, Koolen (1974) used the mean vertical stress, σ_v, instead of the total applied stress, and used the equation

$$\sigma_v = 0.5 (\sigma_t + \sigma_b) \quad (2.19)$$

there σ_t and σ_b are the stress on the top and on the base of container respectively.

Another factor which may influence the result of this test is the friction resistance of the container walls. To minimise this effect, Koolen (1974) established an equation to relate the dimensions of the container to the applied stress

$$\frac{\sigma_b}{\sigma_t} = \left\{\frac{(d/h) - 2 k \tan \delta}{(d/h) + 2 k \tan \delta}\right\} \quad (2.20)$$

where d and h are the diameter and height of the sample, k is an adjustable parameter, and tan δ is the coefficient of sliding fraction between the soil and the container wall material.

With this equation, Koolen (1974) suggested that to obtain meaningful results, the value of d/h should not be less than 2.

Compression tests may also be done in a triaxial cell as has been done by Bailey and Vanden Berg (1968) and Bailey (1971); Dexter and Tanner (1973a) employed the principle of the triaxial apparatus. They prepared cylindrical samples of two sizes: 102 X 102 mm and 38 X 38 mm. The side of the soil sample was enclosed with a rubber membrane which was attached to the metal end plates by O-ring seals. Between the lower ends of the sample and the bottom metal end plate, a porous disc was located. The confining fluid around the sealed soil was water. Hydrostatic pressure was applied ($\sigma_1 = \sigma_2 = \sigma_3$), and the change in the volume of the sample was determined by measuring the volume of the fluid exuded from the bottom of the sample through the porous disc. The results were found to be independent of sample size.

2.2.3 Tensile strength

Soil is considered to fail by tension when separation occurs. The tensile strength of a soil may be defined as the state of stress at which incipient separation occurs. Gill and Vanden Berg (1967) discussed the difficulty in expressing tension failure in precise terms because of the porosity of the soil. The problem is to specify the area over which the force acts, because total area of a soil is made up of air, solid material, and water area. For simplicity, the total area of the soil is usually used.

Tensile strength is usually considered to be a measure of cohesion. When a soil fails in tension, only cohesive forces contribute to the resistance, and thus, at least in principle, it is not subjected to frictional effects (Ingles, 1962). However, this tensile cohesion is not the same as the shear cohesion in equations (2.7 and (2.11). To differentiate cohesion measured by tension from the "shear cohesion", this type of cohesion is called "interparticle cohesion" in this thesis. Tensile strength, σ_T, is on the abscissa and shear cohesion, C, is on the ordinate in Figure 2.3 a, b.

Several factors are responsible for the development of soil tensile strength under field conditions. Haines (1925) suggested that cohesion was made up of (1) true cohesion, and (2) induced or temporary cohesion due to the surface tension of water films. Lambe (1960) identified several types of true cohesion, namely (1) flocculation cohesion, (2) H and K bonding cohesion, and (3) cementation. Mitchell (1976) suggested that the true cohesion might result from (1) cementation, (2) electrostatic-electromagnetic attraction, (3) primary valence bonding, and (4) adhesion. The induced or apparent cohesion does not depend on interparticle cementation or bonding, and it may develop from (1) capillary stress, and (2) apparent mechanical forces.

Cementation between particles can be developed by carbonate, silica, aluminium and iron oxide, and organic materials. These materials may be derived from the soil minerals themselves as a result of weathering processes, or they may be taken from solution. Particle cementation is aided by drying (Lambe, 1960). Not only does drying bring the adjacent particles close enough together to permit cementing, but drying also tends to precipitate soluble cementing materials from the pore water. It has been found that drying tends to result in the production of ferric oxides which are relatively active cementing agents.

Ingles (1962) suggested that the strength of cementing bonds must be a function of (1) the cohesive strength of the cement and/or the substrates itself, (2) the adhesive strength of the cement which is essentially of covalent or ionic bonding, and (3) the area of cement substrate interface. From this reasoning, he developed the equation

$$\sigma_T = P_m \left(\frac{1}{1+e}\right) \frac{n}{\sum_1^n A_i} \qquad (2.21)$$

Here, P is the bond strength per contact zone, m is the mean coordination number of a grain, ΣA_i is the total surface area of the i^{th} grain, n is the number of grains per-unit cross section of failure plane, and e is the void ratio.

Electromagnetic attraction originates from Van der Walls forces. These forces are significant only at separation distance less than 1000

A^o (Ingles, 1962), and vary inversely as the fourth power of the separation distance (Mitchell, 1976). The tensile strength arising from Van der Walls forces for two equal spheres of diameter, d, and separation distance, h, can be computed from

$$\sigma_T = \frac{Am}{24 \pi d h^2 (1 + e)} \tag{2.22}$$

Ingles (1962) suggested that an appreciable tensile strength can be developed by this mechanism only for d < 0.26 μm, that is only for fine montmorillonitic clays, and for separation distance h < 1000 A^o. With these limitations it is likely that the tensile strength arising from Van der Walls is insignificant in most real soils.

The net charge on the plane surface of clay particles differs from that at the edges. The net electrostatic force resulting from this edge/face interaction is attractive. Ingles (1962) computed the tensile strength arising from this force as

$$\sigma_T = k (V_1 - V_2)^2 h^2 \tag{2.23}$$

where $(V_1 - V_2)$ is the potential difference of the surfaces, H is the separation distance, and k is a constant.

When a fluid wets a particulate medium, it is drawn preferentially into the finest capillaries geometrically available to it. Provided that 3 phases are maintained in the system, a considerable force may be required to separate the particles. An attempt to develop a mathematical expression for the cohesion arising from capillary forces was made by Haines (1925; 1927). The Haines's formulae has been discussed by Fisher (1926) and has been applied to study the capillary action in plate shape particles by Nichols (1931). In a later discussion, Ingles (1962) computed the tensile strength arising from capillary forces from

$$\sigma_T = \frac{mn}{(1 + e) \sum_1^n A_i} T \left\{ \left(\frac{1}{r_1} - \frac{1}{r_2}\right) Aj+Cj \ Sin \ (\theta+\Psi) \right\} \qquad (2.24)$$

Where A_j is the planar projected area of the liquid-substrate interface, T is the surface tension of liquid, r_1 and r_2 are the larger and smaller radii of curvature of the liquid/air interface respectively, θ if the contact angle between liquid and solid, and ($\frac{\pi}{2} - \Psi$) is the mean angle of inclination with respect to the applied stress of all tangents to the wetted perimeter.

The potential contributions of various sources of strength discussed above to tensile strength of non-cemented soils are shown in Figure 2.5.

Tschebotarioff, Ward, and De Philippe (1953) found that the tensile strength of montmorillonitic clays was greater that that of kaolinitic clays. Further, they showed that with increasing addition of sand particles tensile strength increased to a maximum and then decreased. Vomocil and Chancellor (1967) investigated the tensile strength of Yolo silt loam (20.3% plastic limit and 33.1% liquid limit), Yolo silty clay (21.6% plastic limit and 47.1% liquid limit), and Columbia silt loam (non plastic soil). They found that the tensile strength of Columbia silt loam was much lower than that of Yolo silt loam or Yolo silt clay. This difference probably arises from the difference in the content of clays which act as cementing materials. The clay content of Columbia silt loam is only 5.3%, whereas those of Yolo silt loam and Yolo silty clay are 16.6% and 41.4% respectively. It is interesting to compare the tensile strength of Yolo silt loam and Yolo silty clay. At low water content, the tensile strength of Yolo silt loam was greater than that of Yolo silty clay. At high water content, however, the tensile strength

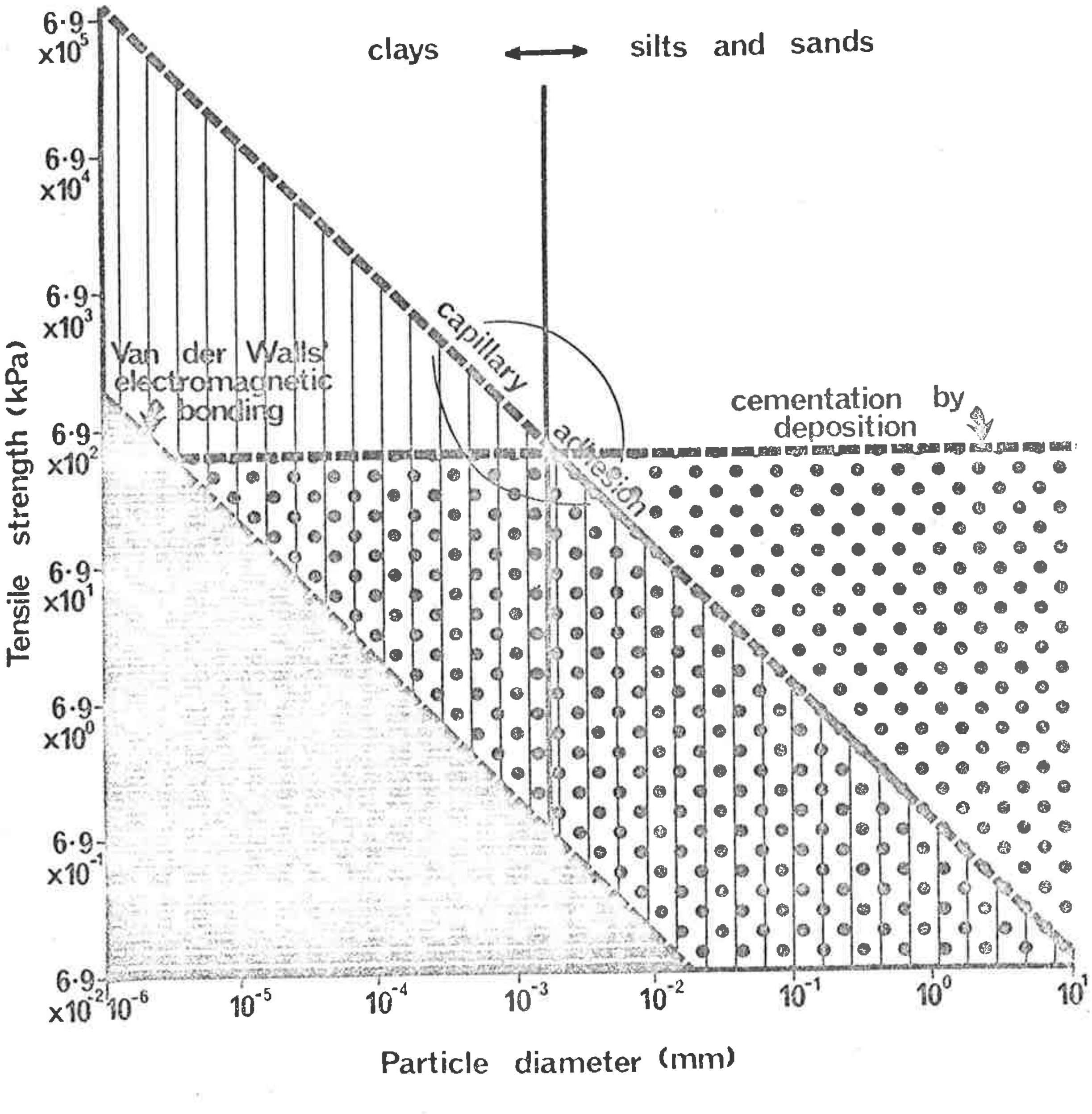


Fig. 2.5. Potential contributions of various bonding mechanism to soil strength (redrawn from Ingles, 1962).

of Yolo silt loam was not different from, or even slightly lower than, that of Yolo silty clay.

Dowdy and Larson (1971) studied the effect of cation type on the tensile strength of montmorillonite, and found that the tensile strength of iron montmorillonite was much greater than that of potassium montmorillonite. A high strength of iron montmorillonite was actually not to be expected, because iron clay is a highly flocculated clay, and hence, larger domains with a reduced area of interdomain contact within a given cross section might be expected. Consequently, the tensile strength should be low. For this result, Dowdy and Larson (1971) reasoned that during cation saturation, small quantities of hydrous iron oxides were formed which served as a cementing agent at the load-bearing areas of contact. This imparted a greater strength to the iron clay than expected.

Vomocil and Waldron (1962) studied effects of water content on the tensile strength of unsaturated glass bead systems. Dowdy and Larson (1970; 1971) found that the tensile strength of montmorillonite decreased with increasing water content. The effect of water content on tensile strength has also been studied by Farrell, Greacen and Larson (1967a) and Vomocil and Chancellor (1967).

The tensile strength of Parafield loam (a red-brown earth) containing 12% clay decreases from about 90 kPa, at about 4% water to about 10 kPa, at about 12% water content (Farrell *et al.*, 1967). In studying the tensile strength of Yolo silt loam, Yolo silty clay, and Columbia silt loam, Vomocil and Chancellor (1967) found that for Yolo silt loam and Yolo silty clay, the tensile strength decreased with increasing water content. For Columbia silt loam, however, there was relatively little influence of water content in the range they used.

Quirk and Panabokke (1962) found that the tensile strength of natural aggregates collected from virgin Urrbrae soil (2.7% organic matter) was greater than that of natural aggregates collected from cultivated Urrbrae soil (1.3% organic matter). The tensile strength of remoulded cores made from these soils, however, was not much different. They, therefore, suggested that the difference in the tensile strength of the natural aggregates from these two soils was not due to organic matter content *per se*, but rather due to the disposition of organic matter in the soil matrix. Rogowski and Kirkham (1976) found that the natural aggregates of Storden (15.1% clay and 0.99 organic matter content), Webster (31.4% clay and 3.26% organic matter content), and Luton (52% clay and 2.96% organic matter content) soils in the air dry condition, had tensile strengths of about 139, 338 and 1016 kPa respectively. When they were equilibrated at -1500 kPa potential, the corresponding tensile strengths were about 27, 23 and 59 kPa.

In addition to the factors discussed previously, the tensile strength of a soil can be reduced by the occurrence of flaws or cracks. The tensile strength of an ideal isotropic material exhibiting no plastic deformation and containing cracks of length 2 ℓ, can be calculated by the well known Griffith's (1921) equation

$$\sigma_T = \sqrt{\frac{(2\ E\ \gamma)}{2\ \ell}} \qquad (2.25a)$$

and

$$\sigma_T = \sqrt{\frac{(2\ E\ \gamma)}{\pi\ \ell\ (1-\nu)^2}} \qquad (2.25b)$$

for plane stress and plane strain conditions respectively. Here E is the Young's modulus, ν is the Poisson's ratio, and γ is the surface energy of the material.

The influence of cracks on tensile strength has been discussed elsewhere (e.g. Ingles and Lafeber, 1966; 1967), and a statistical theory of brittle fracture for soil aggregates has been developed by Braunack, Hewitt and Dexter (1979).

Braunack (1979) tried to relate the tensile strength of soil aggregates to crack length per unit area as observed on thin, impregnated sections. He, however, did not find any significant relationship. To account for this, he reasoned that probably there were invisible cracks which influenced the tensile strength, but which could not be used in calculating the regression.

To measure tensile strength of a soil, Hardy (1925), Gill (1959), and Hendrick and Vanden Berg (1961) employed tension directly upon columns of soil by pulling at the ends. Metcalf and Frydman (1962) and Ingles and Frydman (1963) called this method the "direct tensile stress" measurement. An indirect tension test called the "Brazilian" test which was developed to measure the strength of concrete (Carneiro and Barchelos, 1953) has been used to measure the tensile strength of undisturbed soil cores by Kirkham, De Boodt and De Lenher (1959) and of remoulded soil cores by Metcalf and Frydman (1962) and Ingles and Frydman (1963). In this method, cylindrical soil cores are compressed while lying on their side between parallel plates until a tensile failure occurs. The tensile strength, σ_T, is calculated from

$$\sigma_T = \frac{2\,F}{\pi d l} \qquad (2.26)$$

where F is the force required to fracture the sample, l is the length of the sample, and d is the sample diameter.

Vomocil, Waldron and Chancellor (1961) modified the centrifuge method developed by Haefeli (1951) to measure the tensile strength. They preferred this method because, according to their suggestion, the condition of the sample measured by this method is similar to the field condition in agronomic practice. A block of soil is placed in a centrifuge after which the speed is increased until failure occurs. At failure, the force is calculated from

$$F = m \omega^2 r \qquad (2.27)$$

here, m is the mass of the sample, ω is angular velocity, and r is the radius to the center of the mass.

Vomocil *et al.* (1961) have shown that this method is applicable over a range of water contents from oven dry to that corresponding to approximately -30 kPa matric water potential. This method has been successfully used by Vomocil and Chancellor (1967) to study the tensile strength of some agricultural soils.

In addition to be a measure of the strength of the bulk soil, tensile strength measurement has been found to be very useful to evaluate the tensile strength of soil clods or aggregates (Martinson and Olmstead, 1949; Dexter, 1975; Rogowski and Kirkham, 1976). The measurement of soil clods or aggregates is often necessary because the strength of a soil that has been broken up (by tillage) is not longer homogenous. Dexter (1975) determined aggregate tensile strength by crushing the aggregate between parallel plates. The tensile strength, σ_T, was calculated from

$$\sigma_T = k F/d^2 \qquad (2.28)$$

where F is the force required to fracture the aggregate, d is aggregate diameter, and k is a parameter, the exact value of which can be determined by measurement or by theoretical stress analysis.

Dexter (1975) used a value of k = 0.576. Rogowski and Kirkham (1976) suggested that the value k of 0.821 might be better than k = 0.576.

Besides the tensile strength, several methods have been proposed to measure the strength of soil clods. Marshall and Quirk (1950) used the "drop shatter test", which has been widely used to measure the strength of coals (ASTM, 1946). This method is then used by Lyles and Woodruff (1961) and Bateman *et al.* (1965) to study the energy required to pulverize a soil in tillage practice. A mathematical analysis of this method has been developed by Ingles (1963).

To determine clod strength by the drop shatter test, a clod is dropped from a given height, and then the size distribution of the resulting aggregates is measured by sieving. The result can be simply presented by the relationship between the input energy and the mean weight diameter of the resulting aggregates. The input energy is calculated from the produce of the mass of the clod, the height of drop, and the acceleration of gravity.

Fountaine, Brown and Payne (1956) developed a method to measure the shear strength of soil clods. The clod was coated with wax to prevent it drying, and then cemented at one end into a mould with a quick drying plaster. Then torque was applied to a miniature shear box (which had been pressed into the clod) until fracture occurred. The shear strength is given by

$$\tau_f = \frac{3\,T_q}{2\,\pi\,r^3} \qquad (2.29)$$

where T_q is the torque to cause shear, and r is the radius of the shear box. A similar method was used by Barley (1964) in a study of the shear strength of clods of a red brown earth in South Australia.

Clod strength has also been measured with a laboratory penetrometer by Campbell (1977). He showed that this method is sufficiently sensitive and reproducible to be useful to the study of the strength of clods which are often lifted in potato harvesting.

In addition to the factors discussed previously, it has been shown that the tensile strength of soil aggregates decreases with increasing aggregate size (Rogowski and Kirkham; 1976; Braunack *et al.*, 1979). For this phenomenon, Braunack *et al.* (1979) suggested that large aggregates are made up of several smaller unit volume separated by flaws, such as voids and cracks. Thus the larger is the aggregate, the greater is the probability of it containing a severe flaw. In agreement with Griffith's (1921) theory of brittle fracture, larger aggregates will fracture at a lower stress.

2.2.4 Penetration resistance

Gill and Vanden Berg (1967) considered that the resistance of a soil to probe penetration was a function of a combination of parameters of soil strength. When a probe is pressed or driven into a soil, depending on the shape of instrument used, cutting or separation, shear failure, compression failure, or any combination of these may occur. According to Mulqueen, Stafford and Tanner (1977) the resistance offered by a soil to a penetrometer is a compound parameter involving ocmponents of shear, compressive, and tensile strengths, and soil metal friction. Tensile strength, however, is only involved when the penetration of the probe results in soil cracking, which mainly occurs when the soil is dry (see Figure 11 in Mulqueen *et al.*, 1977). Further, they showed that as the water content of the soil increased, the penetration resistance became increasingly insensitive to shear strength or compressive strength changes. An example of soil flow pattern around a spherical penetrometer tip is given in Figure 2.6 from Dexter and Tanner (1972). This "spherical" type of soil flow also occurs with most other shapes of penetrometer tips.

The tip or probe of penetrometer is often, although not always, larger than the shaft. The total resistance to penetration, therefore,

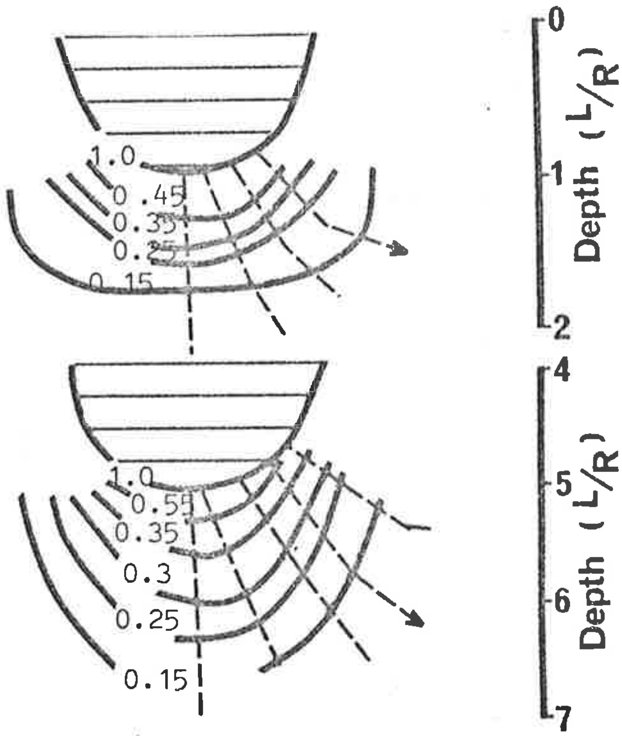


Fig. 2.6. Streamlines and contours of equal particle speed in dry sand (redrawn from Dexter and Tanner, 1972). The numbers give sand particle speeds with respect to that of the sphere. In the top drawing, the sphere is near the sand surface, in the centre drawing, the sphere is deeper.

reflects the soil conditions near the tip. The results are usually expressed as the force or pressure resisting probe penetration at any given depth. Knight and Freitag (1962) and others (e.g. Wismer and Luth, 1974; Voorhees and Walker, 1977) used the "cone index" for the force per unit projected area of a conical probe of 30^{o} total included angle and 323 mm^2 maximum projected area. In this thesis, the term "penetration resistance", Q_p, will be used for the smaller probe used here, and is calculated from

$$Q_p = 4 F/\pi d^2 \qquad (2.30)$$

Here, F is the force required to push the probe, and d is the probe diameter.

With a probe of 1.5 mm diameter and 60^{o} tip angle, Barley, Farrell and Greacen (1965) found that the penetration resistance offered by a soil in both confined and unconfined cores of 3.6 cm diameter and 2.0 cm height increased with increasing penetration depth up to 5 mm. For confined cores, a further increase in penetration depth was not followed by any change in the penetration resistance, and for unconfined core, due to crack formation, the penetration resistance decreased rapidly with increasing penetration depth. Dexter and Tanner (1973b) found that with increasing penetration depth, the force required to push the penetrometer increased towards a maximum limiting value, and could be described adequately by the equation

$$F = A + B e^{-k(L/R)} \qquad (2.31)$$

where A, B, and k are adjustable parameters, and L/R is the dimensionless depth of penetration measured in spere radii. They found that the force is nearly constant when the penetration depth had reached the value of L/R = 4.

Following Nishida's (1961) approach, Farrell and Greacen (1966) developed a mathematical analysis of probe penetration in a compressible soil. Assuming that the principal stresses in the soil adjacent to the probe are the radial and tangential stresses, σ_{ra} and σ_{ta}, required to form a spherical cavity, then the normal stress, σ_N on the basal surface of the probe is given by

$$\sigma_N = \tfrac{1}{2}(\sigma_{ra} + \sigma_{ta}) + \tfrac{1}{2}(\sigma_{ra} - \sigma_{ta}) \text{ Cos } \Psi \qquad (2.32a)$$

and

$$\tan \delta = (\sigma_{ra} - \sigma_{ta}) \text{ Sin } \Psi/_2\, \sigma_N \qquad (2.32b)$$

where

$$\sigma_{ra} = A\,(1 + \sin\emptyset)\,(^R/r)^{4 \sin \emptyset\, (1 + \sin \emptyset)} + B$$

$$\sigma_{ta} = A\,(1 - \sin\emptyset)\,(^R/r)^{4 \sin \emptyset\, (1 + \sin \emptyset)} + B$$

Here, $\emptyset$ is the angle of soil internal friction, δ is the angle of soil/metal friction, Ψ is the direction of the principal stresses, R is the radius of the sphere of the plastic zone, r is any radial distance from the point of the probe, and A and B are arbitrary constants to be determined.

The penetration resistance is then,

$$Q_p = \sigma_N\,(1 + \tan \delta \;\cot \alpha) \qquad (2.33)$$

where α is the included semi angle of the probe point.

As a measure of soil strength, penetrometer resistance has been found to be very useful in many scientific diciplines. Stone and Williams (1939) used a penetrometer to predict the draft force of ploughs in various soil conditions. Knight and Freitag (1962) and others (e.g. Wismer and Luth, 1974; Voorhees and Walker, 1977) related penetration resistance to trafficability. Penetrometers have been used by many wokers to study effects of soil strength on the growth of plant roots (e.g. Barley *et al.*, 1965; Taylor, Roberson and Parker, 1966; Dexter, 1978). An excellent review of this subject has been published by Barley and Greacen (1967).

The penetrometer discussed here must be differentiated from the "drop cone penetrometer" discussed in section 2.2.1. The simplest type of penetrometer is that called the "static penetrometer". To measure soil strength, the penetrometer is just pushed to any given depth, and the strength of the soil is usually recorded as the cone index or penetration resistance as discussed previously.

To obtain a continuous reading with depth, several types of recording penetrometer have been developed (e.g. Hanks and Harkness, 1956; Barley *et al.*, 1965; Dexter and Tanner, 1973b; Prather, Hendrick and Schafer, 1970; Anderson *et al.*, 1980). The root simulation penetrometer assembled by Barley *et al.* (1965) consisted of a penetrometer probe and shaft driven by an electric motor. The force was measured with small proving ring equipped with electrical resistance strains gauges. Each gauge was calibrated by dead load tests. Force was recorded as a function of depth of penetration with a milivolt recorder. This was essentially the penetrometer used in the work described in this thesis. However, here the force was measured by an electronic digital balance (Mettler model PC 4400), which gave greater accuracy and repeatability.

A hand held recording penetrometer developed by Anderson *et al.* (1980) called the "Solid state penetrometer" is capable of measuring force up to 500 ± 5N. The force is measured with strain gauge transducer, and the depth is measured by an accurate optical system. This penetrometer can be equipped with a programmable calculator which enables the accumulation of data up to 20 strokes per plot. On interogation, the calculator displays for each depth: the mean cone index, the standard deviation, and the number of strokes recorded at that depth.

The rate of penetration, probe diameter, and the angle of penetrometer tip have been found to be among the factors influencing penetration resistance. Cockroft, Barley and Greacen (1969) found that the resistance of a soil to probe penetration was inversely related to the rate of penetration. With a probe of 2 mm diameter and 60^{o} included angle, they found that the penetration resistance of remoulded B horizon Urrbrae soil (64.9% clay) were 1900, 1720, 1510, and 1040 kPa when the probe was pushed downward at the rate of 0.175 mm/hr, 1.75 mm/hr, 10 mm/hr, and 60 mm/hr respectively. With a 20 mm diameter spheres, Dexter and Tanner (1973b) found that on clay (62% clay and 24% silt), clay with chalk (46% clay and 30% silt), and loam with peat (26% clay and 36% silt) soils, the maximum limiting force increased linearly with increasing penetration rate from 0 to 1000 mm/hr. For sandy loam soil (10% clay and 18% silt), the maximum limiting force decreased exponentially as the rate of penetration increased.

Using steel spheres with a penetration rate of 20 mm/sec, Dexter and Tanner (1973b) found that the maximum limiting force varied as the square of the sphere radius:

$$F = a + br^2 \qquad (2.34)$$

This has the implication that the pressure

$$Q_p = \frac{a}{\pi r^2} + \frac{b}{\pi} \qquad (2.35)$$

tends to infinity as the probe radius tends to zero. With relieved, conical probes of 30^{o} semi-angle, Gooderham (1973) found that the penetration resistance of 1 mm diameter probe was 35-74% larger than that of 2 mm diameter probe.

Mulqueen *et al.* (1977) investigated the effect of probe angle on the maximum limiting force. They used the NIAE recording soil penetrometer which was equipped with two probes, i.e. (1) a blunt probe consisting of a hardened steel spheres of radius 10.0 mm, and (2) a sharp probe consisting of a hardened steel 30^{o} right circular cone with base radius of 10.1 mm. They found that in the non plastic state and at low bulk density, the limiting force on the blunt sphere was significantly higher than that in the sharp cone. This difference becoming non-significant as the bulk density and/or the water content of the soil increased.

The effect of probe material on the maximum limiting force has been investigated by Dexter and Tanner (1973b). They measured the force acting on 20 mm diameter spheres having surface of steel, polytetra-fluorethylene (PTFE), and 0.7 mm diameter sand grains. It was found that the average maximum limiting forces for clay, clay with chalk, loam with peat, and sandy loam soils were 182, 193, and 212 N for PTFE, steel, and sand covered respectively. In terms of the angle of soil/metal friction, δ, they obtained equations

$$F = 146 + 80 \tan \delta \text{ N} \qquad (2.36)$$

at 100 mm/sec. penetration rate, and

$$F = 149 + 76 \tan \delta \text{ N} \qquad (2.37)$$

at 20 mm/sec. penetration rate.

It has been found that the resistance of a soil to probe penetration is influenced by soil texture, bulk density, and soil water content (Taylor *et al.*, 1966; Mirreh and Ketcheson, 1972; Becher, 1978; Byrd and Cashel, 1980). Taylor *et al.* (1966) have shown that at a bulk density of 1.55 g/cm^3 and matric water potential of -33 kPa, Miles loamy fine sand (9% clay) has a penetration resistance of about 800 kPa, whereas Columbia loam (19% clay) has a penetration resistance of about 18 kPa.

Byrd and Cassell (1980) found no simple relationship between percentage of sand and cone index. At a matric water potential of -6 kPa, cone index values increased with increasing sand content. At a matric water potential of -33 kPa, cone index values increased as percentage sand increased from 66.6% to 75.4%, decreased from 75.4% to 79.2%, and then again increased from 79.2% to 82.2%.

The resistance of a soil to probe penetration decreases with increasing water content (Taylor *et al.*, 1966; Mirreh and Ketcheson, 1972), and with decreasing soil bulk density (Taylor *et al.*, 1966). At -33 kPa matric water potential, the penetration resistance of Columbia silt loam is about 1800, 900, and 700 kPa for bulk densities of 1.55 g/cc, 1.35 g/cc, and 1.25 respectively (Taylor *et al.*, 1966). Mirreh and Ketcheson (1972) found that at low bulk density the increase in matric water potential, first (up to -400 kPa) increased the penetration resistance, then a further increased in matric water potential decreased the penetration resistance. At high bulk density, increasing matric water potential increased the penetration resistance sharply without any subsequent decrease in penetration resistance. The decrease in penetration resistance with increasing soil water content has also been shown by Becher (1978) and Byrd and Cassell (1980).

With a 1.5 mm diameter probe, Becher (1978) found that the penetration resistance of soil cores prepared from Pelosols, was negatively correlated with organic matter content. Based on this result, he suggested that to provide a good medium for root growth it was necessary to maintain or increase organic matter to reduce penetration resistance in Pelosols.

SECTION 3

THIXOTROPIC HARDENING

3.1 Effect of ageing on the strength of remoulded soils

3.1.1 Introduction

Remoulding an undisturbed soil, except for a soil that has been overconsolidated, usually results in a loss of part of its strength. This phenomenon was first observed in some Norwegian and Canadian clays which are known as "sensitive" or "quick" clays. Rosenqvist (1952) has observed that the shear strength of a soil which is initially in excess of 10 - 20 kPa may be reduced to less than 0.1% of this value by remoulding. The ratio of undisturbed strength to the remoulded strength is known as the "sensitivity" (Terzaghi, 1944).

According to Terzaghi (1941) the close approach of particles as a result of squeezing out of viscous absorbed water from points of contact leads to high attraction forces. When this soil is remoulded, the interparticle contacts breakdown, and adsorbed water fills in around the old contacts with a consequent decrease in strength. Some workers (Winterkorn and Tschebotarioff, 1947; Yasutomi and Sudo, 1966; Smalley, 1978) suggested that the decrease in strength of undisturbed soil with remoulding is due to the breakdown of the connecting links and cementing bonds between particles. In addition to these processes, Mitchell (1960) has postulated that the lower strength of a remoulded soil is due to the change in the energy status of the system resulting from particle rearrangement.

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

The phenomenon of strength regain in a soil is time dependent. Mitchell (1960), therefore, defined thixotrophy 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.

It is necessary to point out that not all strength regain in aged soil results from thixotropic processes. Mitchell (1976) suggested that thixotropic hardening contributes to the strength regain up to the sensitivity of 8. Beyond this value, another mechanism, such as the formation of permanent cementing bonds (Bjerrum and Lo, 1962), must exist. Because of this, some workers (Yasutomi and Sudo, 1966; Smalley, 1978) preferred to use the term "age hardening" instead of thixotropic hardening.

It seems that Moretto (1948) was the first scientist to study in detail the strength regain of remoulding clays resulting from ageing at constant water content. He rejected a common theory which assigned most of the differences in the strength between undisturbed and remoulded clays to an irreversible loss of structure. A similar conclusion was obtained by Skempton and Northey (1952) in studying the processes involved in causing the sensitivity in some clays. Seed and Chan (1957), Mitchell

(1960) and Gray and Kashmeery (1971) have presented excellent discussions on thixotropy in compacted soils.

Blake and Gilman (1970) and Arya and Blake (1972) studied thixotropic processes from the point of view of aggregate water stability. It has been found that ageing increases the water stability of newly formed synthetic aggregates (Blake and Gilman, 1970), and of the aggregates formed by plough shearing of field soil and by particle coalascence around water drops (Arya and Blake, 1972). These workers suggested that this phenomenon is analogous to a thixotropic sol-gel transformation and to an increase in the strength of remoulded soil with ageing.

Thixotropy is related to the balance of forces acting between particles, and therefore, it is influenced by the magnitude of attraction and repulsion forces (Freundlich, 1935). This concept has been widely supported by many workers, including Lambe (1953). Mitchell (1960) illustrated this concept as shown in Figure 3.1. The ordinate of this curve represents the energy (positive if repulsion and negative if attraction) necessary to bring particles from an infinite spacing to any given spacing along the abcissa. Curve A represents a stable suspension which exhibits neither flocculation nor thixotropy because of the energy barrier preventing close approach of particles. Curve B represents a condition where particles will spontaneously agglomerate and settle out. The energy minimum indicated on curve C represents the spacing of the particles in a thixotropic gel. Any movement, such as caused by shaking or shearing, which tends to change the particle spacing causes an increase in energy of repulsion leading to a more fluid condition.

An interesting approach to the description of the thixotropic process is to consider the changes in the water energy status of the system. Croney and Coleman (1954) and others (Day and Ripple, 1966;

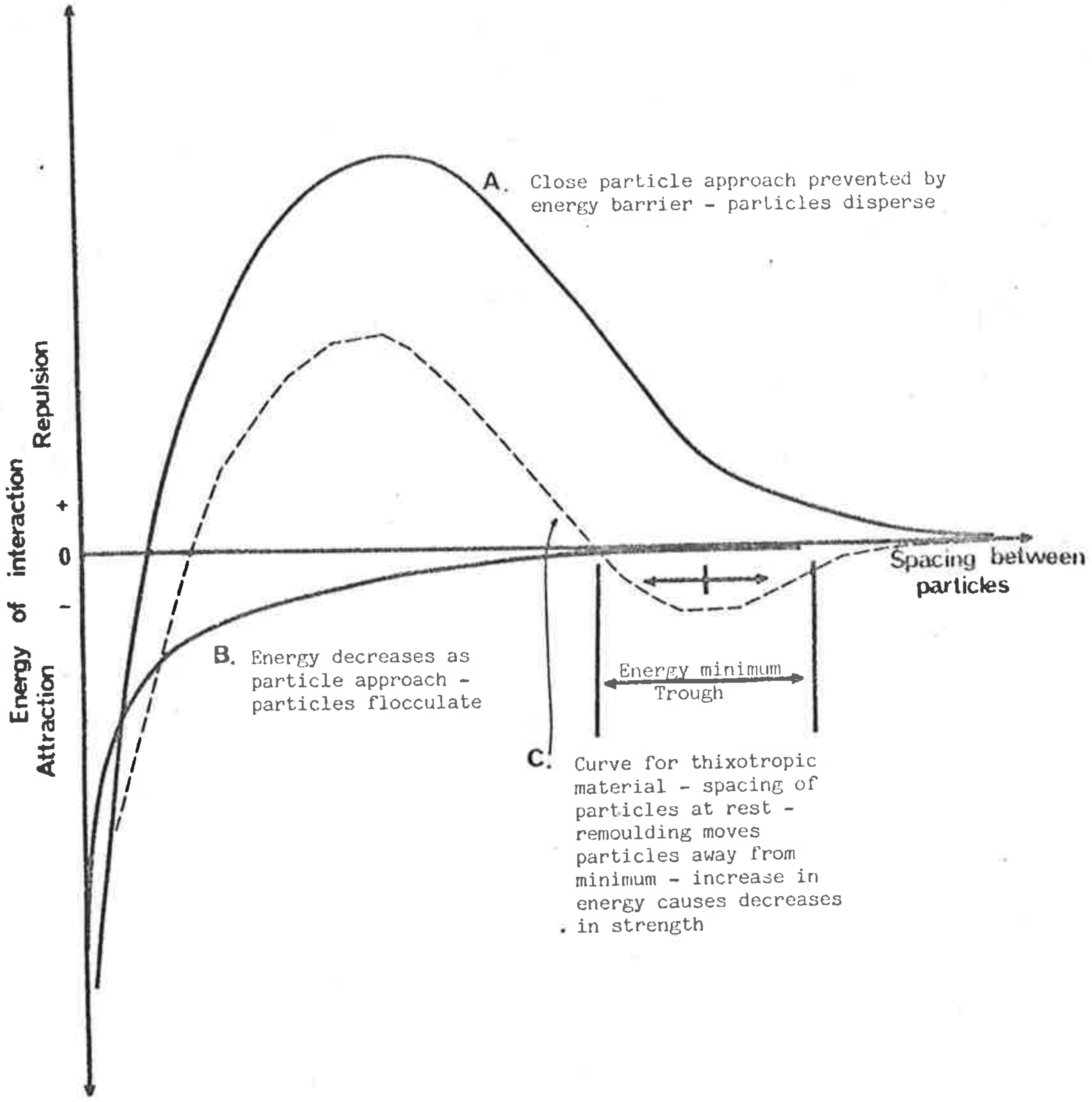


Fig. 3.1. Energy distance curves for dilute suspensions of dispersed, flocculated and thixotropic materials (redrawn from Mitchell, 1960).

Schweikle, Blake and Arya, 1974) found that shearing or remoulding a soil result in a less negative matric water potential. When the soil is then allowed to rest, the matric water potential becoming more negative. Mitchell (1960) interpreted these data in terms of cohesion forces. He pointed out that shearing decreased cohesion forces as shown by the decrease in the viscosity of the system, and allowing the gel to rest resulted in an increase in the cohesion forces. This was shown by the fact that the gel viscosity changes to its initial viscous state as the potential was restored. This approach has also been treated by Yasutomi and Sudo (1966).

Trollope and Chan (1960) suggested that thixotropic strength regain in compacted soil is due to changes in disposition of the colloidal particles within the soil mass. The hypothesis of structural changes with ageing which cause thixotropic strength regain has also been put forwarded by Mitchell (1960), Yasutomi and Sudo (1966) and Gray and Kashmeery (1971). Mitchell (1960) suggested that when a thixotropic soil is remoulded or compacted, a part of the externally-applied shearing energy is utilized to disperse the platy clay particles into uniform, parallel arrangement. Thus at this stage, the external applied energy assists the repulsive forces between particles resulting from double layer interaction in producing a dispersed system, with a consequent low strength. As soon as shearing ceases, the external applied stress, which was assisting repulsive forces, drops to zero. Thus the net repulsive forces decrease, and now the attractive forces exceed the repulsive forces for the particular arrangement of particles and distribution of water. As a consequence, the structure attempts to adjust itself into a new relative lower energy condition, which results in an increase in the strength. This concept is consistent with the ideas of Croney and Coleman (1954), Day and Ripple (1966), Yasutomi and Sudo (1966), and

Schweikle *et al.* (1974) discussed previously. Gray and Kashmeery (1971) tried to freeze the microstructure of a thixotropic soil at various ageing times by impregnating some of their samples with carbowax, and then analysing them by X-ray diffraction. However, they couldn't differentiate between X-ray diffactograms of compacted clay samples at time zero and one month later.

According to Mitchell (1960), a soil will exhibit thixotropic behaviour it meets the following conditions: (1) the net interparticle force balance is such that the soil will flocculate if given a chance, and (2) the flocculation tendency must not be so strong that it cannot be overcome by mechanical action, such as shearing or remoulding the soil. This second condition is consistent with the result of Furukawa and Kawaguchi (1969) who found that thixotropic behaviour was found only in soils containing aggregates of low to moderate stability, and not in well stabilized soils containing cementing materials or high organic matter content.

As discussed previously the formation of cementing bonds with ageing may also make a significant contribution in increasing the strength of aged soil. The partial conversion of hydrogen montmorillonite to aluminium forms has been found by Mathers, Weed and Coleman (1955). Martin (1958) has shown that after ageing for 100 days at 70^{o}C, lithium kaolinite changes to aluminium kaolinite. These processes, however, alter the condition of the system, so this hardening process cannot be classified as thixotropy according to the definition of Mitchell (1960).

In this thesis, the interest is not only in the strength regain resulting from thixotropic hardening, but in all processes leading to an increase in the strength of aged, remoulded soil. The term "thixotropic hardening" is used if the condition of the system meets Mitchell's (1960) criteria, otherwise the broader term "age hardening" is used.

3.1.2 Materials and Methods

Soils

The soils used were three sandy loams from South Australia, and a clay soil from Queensland. The South Australia soils were collected from the Urrbrae fine sandy loam, from the Charlick experimental station at Strathalbyn, and from the Mortlock experimental station. All these fields belong to the Waite Institute. The Queensland soil is the Waco soil from Jondaryan.

The Urrbrae and Mortlock soils are red brown earths, 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, Fox and Hughes, 1973). Some properties of these soils are given in Table 3.1.

Table 3.1. Compositions and Atterberg limits of the soils used in the experiment.

Soil site	Proportion of oven dry soil <20 μm (%)	<2 μm (%)	org. matter (%)	clay mineral	Plastic limit (%)	Liquid limit (%)
Urrbrae	49	17	1.7	illite kaolinite	19.5	26.5
Mortlock	46	17.5	3.6	illite kaolinite	23.9	36.5
Strathalbyn	36	12	2.8	illite actinolite	17.9	30
Waco	87	74	1.9	montmorillonite	54	86

Remoulding

Samples from the A horizon of those soils were passed through a 1 mm sieve, then remoulded with deionized water at several water contents from slightly below the plastic limits up to nearly the liquid limits. Remoulding was done with a laboratory knife until the soils were as homogeneous as possible. These remoulded soils were allowed to equilibrate overnight, then again remoulded for about 2 minutes and pressed in plastic containers of 24 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 remainders, in their containers, were wrapped in thin plastic sheeting and aluminium foil, then stored in a constant temperature room 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^{o}, and penetrated downward at a rate of 3 mm min^{-1}. The force required to penetrate the soil was measured with an electronic digital balance Mettler type PC 4400 (Plate 3.1).

Three measurements were done on each core, thus there were 6 - 9 measurements at each water content for each soil. The measurement was done to a depth of 5 mm. This was based on the finding of Dexter and Tanner (1973) which showed that the limiting maximum penetration force attains a constant value for depths of penetration L/R greater than four times the probe size. The strength was calculated as the resistance to probe penetration, Q_p, using equation

$$Q_p = 4 F/_{\pi} d^2 \qquad (3.1)$$

where F is the force required to penetrate the sample, and d is the probe diameter.

Plate 3.1. Measurement of soil strength with a laboratory penetrometer.


Mettler PC 4400

Each time after testing, the sample was remoulded, pressed back into container and its strength was measured. When this remoulded strength was equal to that of remoulded sample at time of preparing the specimen (0 day sample), the strength increase could be considered as a thixotropic hardening. Any change in this remoulded strength would indicate some permanent alteration, such as the formation of permanent cementing bonds. When this occurs, the term thixotropy cannot be applied.

To test whether there was any change in soil water content, each time after measurement of the strength, the water content of the sample was determined. When there was a significant change in water content, the result was discarded.

3.1.3 Results and Discussion

Effect of water content on soil strength

The effect of water content at remoulding on packing density and soil strength is given in Figure 3.2. Packing density, D, was defined as the volume proportion of the soil which is occupied by solid particles,

$$D = \frac{\rho}{\rho_m} \left(\frac{100 - \%\ \text{organic matter}}{100 + \%\ \text{water content}} \right) \qquad (3.2)$$

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

Figure 3.2 shows that unlike packing density, which increases with increasing water content up to a maximum value and then decreases on further water content increases, the penetration resistance decreases steadily with increasing water content. Over the range of water content used, the logarithm of the soil strength is an approximately linear function of soil water content (here expressed as a proportion of plastic limit, PL)

$$\log_e Q_p = A - a \left(\frac{W}{PL} \right) \quad (3.3)$$

The value of adjustable parameters A and a, together with the strength at the plastic limit, Q_p 1.0, are given in Table 3.2. For comparison, the value of parameters A and a, and Q_p 1.0 of Urrbrae field clods are also given in Table 3.2 and Figure 3.2. 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 plate apparatus 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, at least, 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.

Table 3.2. Values of A and a parameters of equation (3.3), and the strength at the plastic limits, Q_p 1.0, for the freshly remoulded Urrbrae, Strathalbyn, Mortlock and Waco soils, and the field clods collected from the Urrbrae soil.

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
Mortlock	13.86	7.37	0.99	663.5
Waco	11.81	4.32	0.98	1790.1

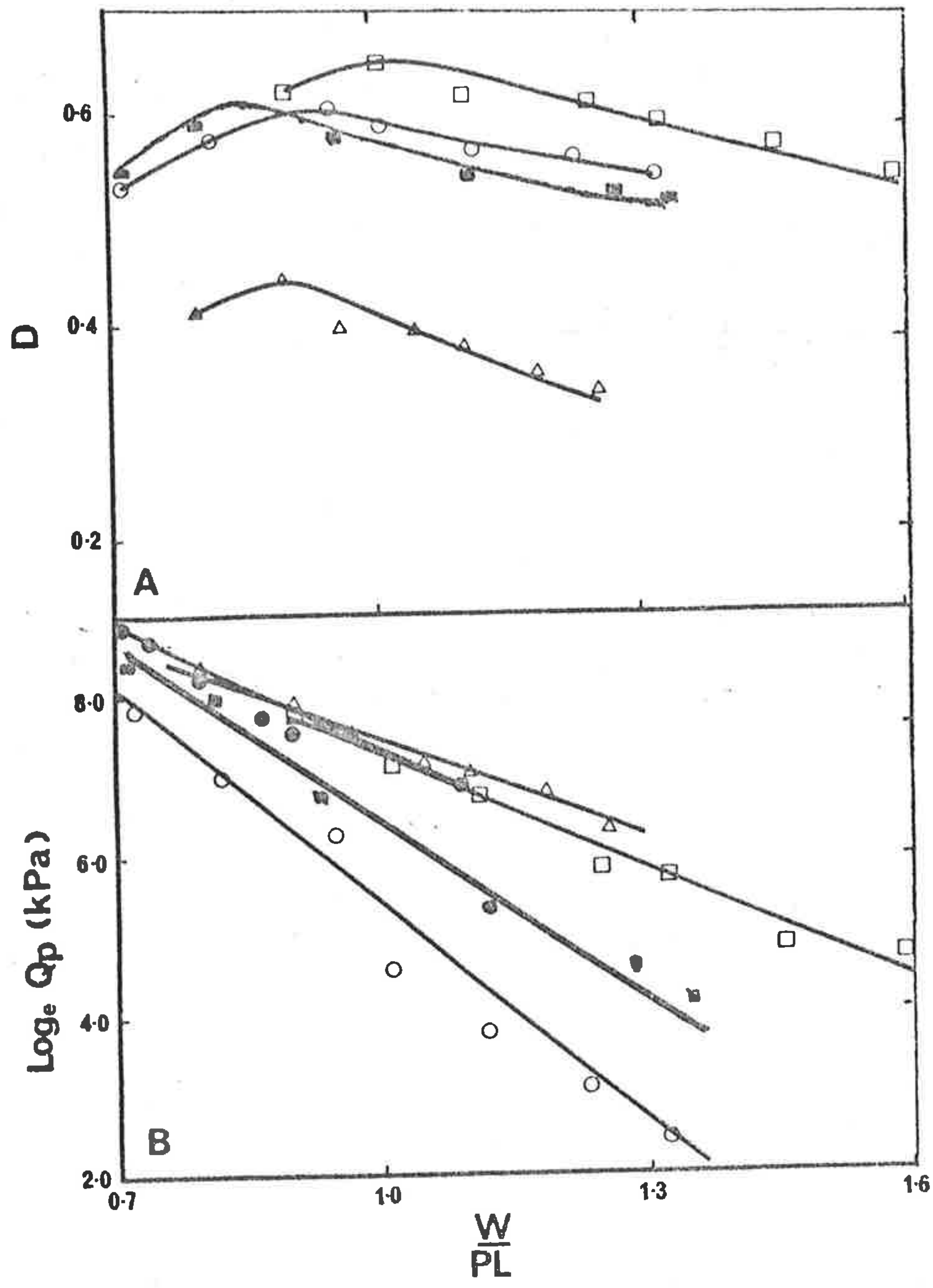


Fig. 3.2. Effect of water content ($\frac{W}{PL}$) on soil packing density (D) and on soil penetration resistance (Q_p).

○: Urrbrae remoulded; ●: Urrbrae field clods; □: Strathalbyn; ■: Mortlock; △: Waco.

Effect of ageing on soil strength

Ageing of the remoulded Urrbrae, Strathalbyn, Mortlock and Waco soils resulted in an increase in the resistance of the soil to probe penetration (Table 3.3). It was observed that the strengths of the samples remoulded after ageing were about the same as that of the 0 day sample. In addition, as shown in Table 3.3, the change in water content and packing density of the sample was negligible. Thus the criterion of the system met Mitchell's (1960) criterion for a thixotropic process, and hence the mechanism of strength regain which occurred in this experiment could be described as a thixotropic hardening. The effect of ageing up to 30 days on the strength of the Urrbrae, Strathalbyn and Waco soils is given in Figure 3.3.

To test the truth of the above suggestion a further experiment was designed to eliminate other processes which may contribute the strength increase with ageing. In the following experiment, the formation of cementing bonds caused by organic matter and microbial activity was minimized. This was done by destroying organic matter and sterilizing the Urrbrae soil.

Oxidation was done with hydrogen peroxide (Robinson, 1922), and sterilization was done by mixing the soil with sodium azide and mercuric chloride, 0.5 mg of NaN_3 and 0.5 mg of $HgCl_2$ per gram of soil (Tisdall *et al.*, 1978). The ATP test (Jenkinson and Oades, 1979) showed that there was no contamination in sterilized samples.

Ageing of both oxidized and sterilized soils resulted in strength increases as shown in Table 3.4. However, the strength of oxidized and sterilized soils, especially for the non-aged sample (0 day sample), is much lower than that of untreated soil. Quirk and Panabokke (1962) showed that the crushing strength of natural aggregates from a virgin

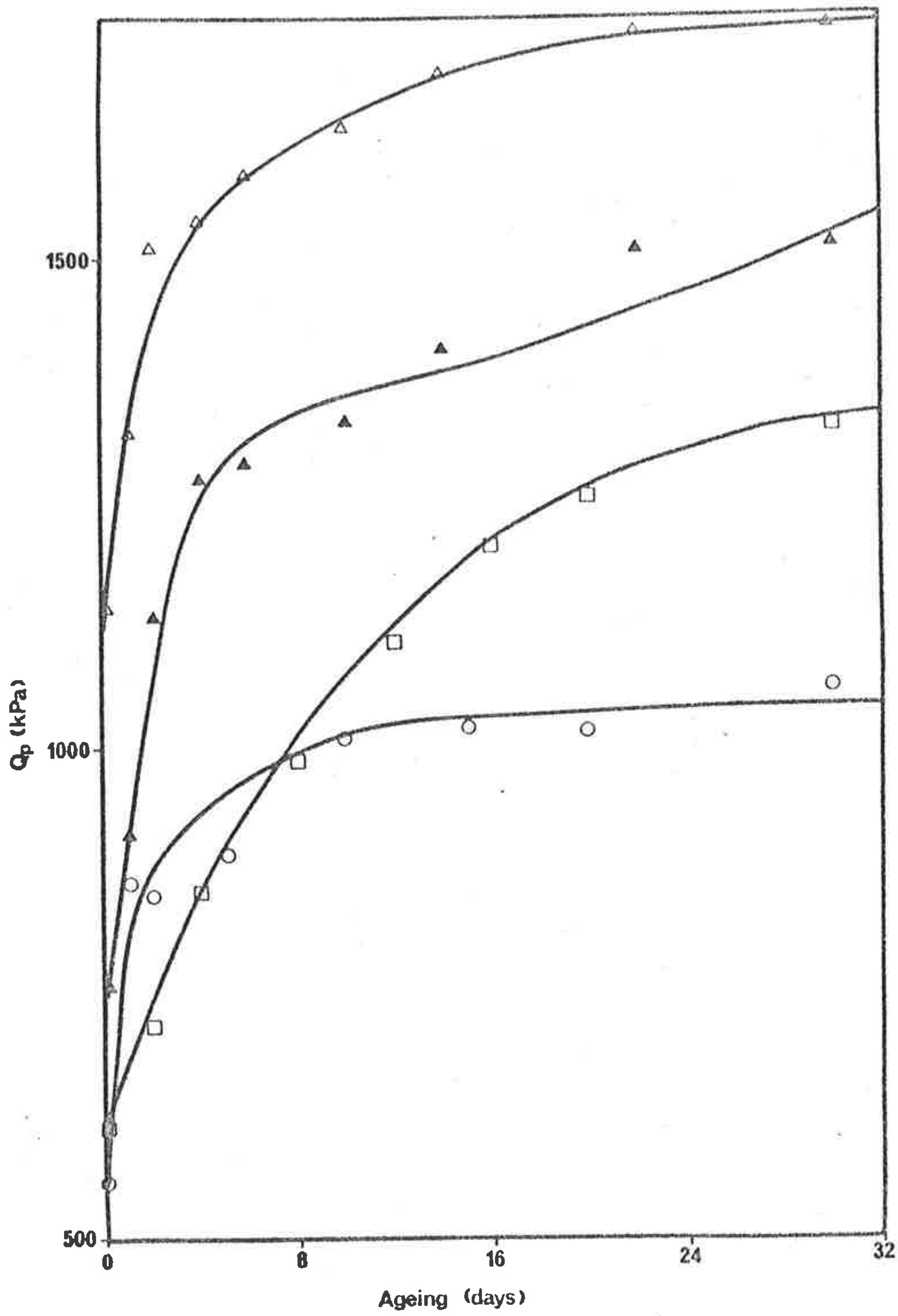


Fig. 3.3. Effect of ageing on the resistance to probe penetration (Q_p) of remoulded soil.
o: Urrbrae (W = 18.5%); □: Strathalbyn (W = 21.4%);
△: Waco (W = 57.3%); ▲: Waco (W = 62.5%).

Table 3.3a. 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	14.24	0.534
	16	1099.9	16.39	0.575
	18	591.4	18.24	0.600
	20	103.3	19.98	0.584
	22	42.3	21.97	0.573
	24	22.0	24.14	0.560
	26	12.5	25.99	0.546
6	14	2722.7	14.31	0.540
	16	1880.9	16.17	0.572
	18	976.3	18.03	0.596
	20	131.1	19.97	0.587
	22	65.1	21.96	0.574
	24	23.8	23.90	0.560
	26	12.0	25.86	0.550
12	14	2688.0	14.28	0.536
	16	2054.3	16.28	0.572
	18	1062.4	18.07	0.603
	20	183.5	20.30	0.580
	22	71.6	22.04	0.570
	24	28.8	23.98	0.563
	26	13.3	25.42	0.548

Table 3.3b. 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	16.34	0.624
	18	1344.3	18.00	0.645
	20	839.8	19.53	0.616
	22	352.6	22.31	0.613
	24	322.5	24.07	0.590
	26	125.6	26.04	0.574
	28	111.3	28.65	0.538
6	16	3703.1	16.61	0.626
	18	2170.4	18.09	0.639
	20	1424.8	20.04	0.616
	22	633.0	22.73	0.611
	24	641.8	23.92	0.586
	26	231.8	26.09	0.570
	28	182.1	28.40	0.538
12	16	4174.8	16.78	0.620
	18	2331.1	18.45	0.647
	20	1561.7	20.10	0.624
	22	708.1	22.63	0.616
	24	650.4	23.71	0.590
	26	245.3	26.14	0.571
	28	193.1	28.15	0.540

Table 3.3c. Effect of ageing on the penetration resistance, Q_p, of remoulded Mortlock soil.

Ageing (days)	Water content at remoulding (%)	Q_p (kPa)	Water content after testing (%)	Packing density
0	16	4967.0	16.95	0.543
	19	3828.1	19.45	0.585
	22	836.7	22.67	0.573
	26	245.9	26.28	0.548
	29	99.9	30.33	0.524
	32	58.6	32.04	0.513
3	16	5722.1	16.45	0.548
	19	4307.2	19.62	0.583
	22	996.4	22.48	0.576
	26	275.7	26.04	0.551
	29	110.6	29.96	0.530
	32	65.3	32.24	0.516
12	16	5821.6	16.76	0.547
	19	5382.1	19.51	0.586
	22	1426.9	22.35	0.577
	26	469.1	26.00	0.552
	29	143.6	30.13	0.528
	32	90.1	31.98	0.514

Table 3.3d. 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	43.93	0.410
	48	2494.9	48.36	0.422
	52	1859.4	51.97	0.394
	56	1416.5	56.45	0.390
	60	1160.2	59.70	0.377
	64	864.2	63.97	0.355
	68	620.5	67.30	0.336
6	44	5074.1	44.55	0.410
	48	3900.8	49.25	0.420
	52	3110.1	52.60	0.396
	56	2384.2	56.55	0.392
	60	1954.6	60.21	0.381
	64	1472.4	64.21	0.360
	68	964.6	67.54	0.339
12	44	5026.0	44.17	0.406
	48	3867.0	49.56	0.416
	52	3426.8	52.43	0.390
	56	2783.9	57.24	0.384
	60	2336.8	60.58	0.376
	64	1844.6	64.17	0.358
	68	1031.8	67.18	0.343

plot of the Urrbrae soil (2.7% organic matter content) is greater than that of aggregates from a cultivated plot (1.3% organic matter content) over the range of water content they used. The crushing strength of remoulded cores prepared from these 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 from Pelosols decreased with increasing organic matter content over a range of water matric potential of -5 to -40 kPa. For natural aggregates, at water potentials less negative than -4 kPa the penetration increased with increasing organic matter content, whereas in drier soils the increase in organic matter content did not give a consistent effect. The results in Table 3.4 cannot be compared directly with those of these earlier works, 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). They, however, did not investigate the thixotropic process in terms of strength, but preferred aggregate water stability. They showed 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 sample from 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.

Table 3.4. Effect of organic matter oxidation and sterilization on the strength of remoulded Urrbrae soil.

Ageing (days)	Water content* (%)	Q_p (kPa) control	oxidised	sterilised
0	17	757.7	345.0	329.5
	20	136.3	55.5	110.0
	22	48.1	5.9	5.1
1	17	1300.8	626.8	560.8
	20	188.6	78.1	148.8
	22	64.5	8.4	7.9
2	17	1348.2	798.2	562.0
	20	218.4	81.5	156.3
	22	64.0	12.8	8.0
4	17	1523.9	874.0	629.5
	20	218.2	87.4	176.8
	22	64.7	15.3	7.2
8	17	1618.4	1487.9	624.4
	20	221.6	108.5	182.0
	22	74.2	20.3	7.7
15	17	1627.3	1546.0	660.6
	20	220.2	180.1	187.3
	22	68.2	28.3	7.3

* The water contents of the samples were not these exact values but were close to these values. For simplicity, however, this method of presentation is used.

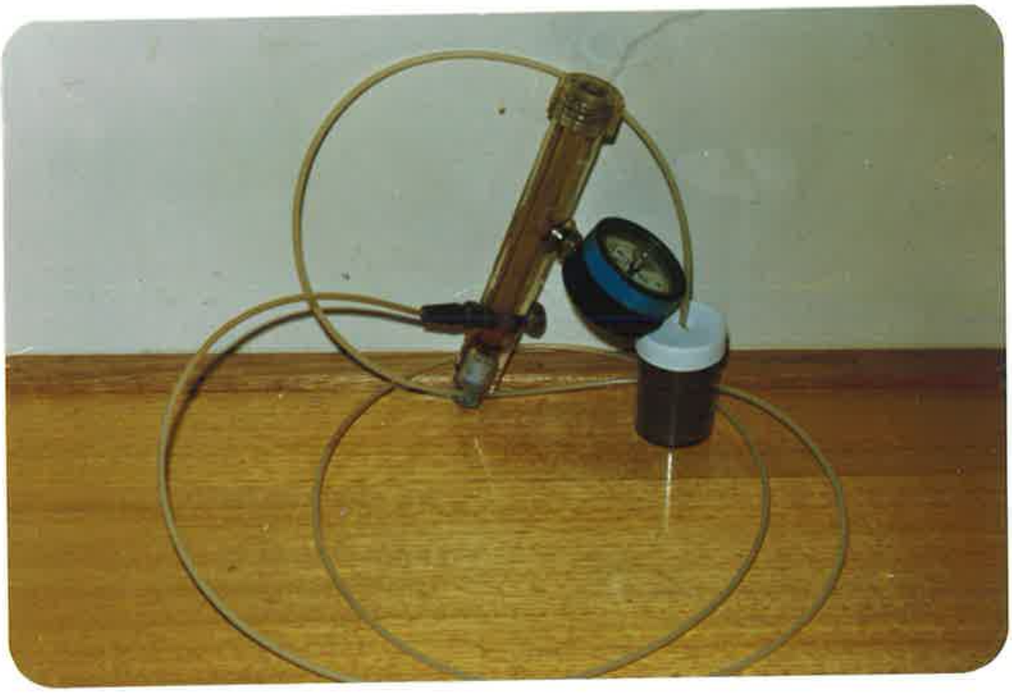
Schweikle *et al.* (1974) found that even in the absence of microbial activity, there was a change in matric water potential with ageing (matric water potential becoming more negative). They concluded that thixotropic behaviour was independent of microorganisms.

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

Samples of Urrbrae and Waco soils were remoulded at about 20% and 65% water content respectively. For the Waco soil, remoulding was done with and without sterilization. After allowing the soils to equilibrate overnight, the soils were again remoulded and pressed 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 RTV sealant to make it air tight (Plate 3.2). The cores were then stored in a constant temperature room (20^{o}C). Two samples were prepared for each treatment.

The result (Figure 3.4) 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 content 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 the strength. A similar result has been shown by Croney and Coleman (1954), Day and Ripple (1966) and Schweikle *et al.* (1974). Bodman and Day (1943), and Campbell (1952) on the other hand, found that

Plate 3.2. Measurement of matric water potential with a soil tensiometer.



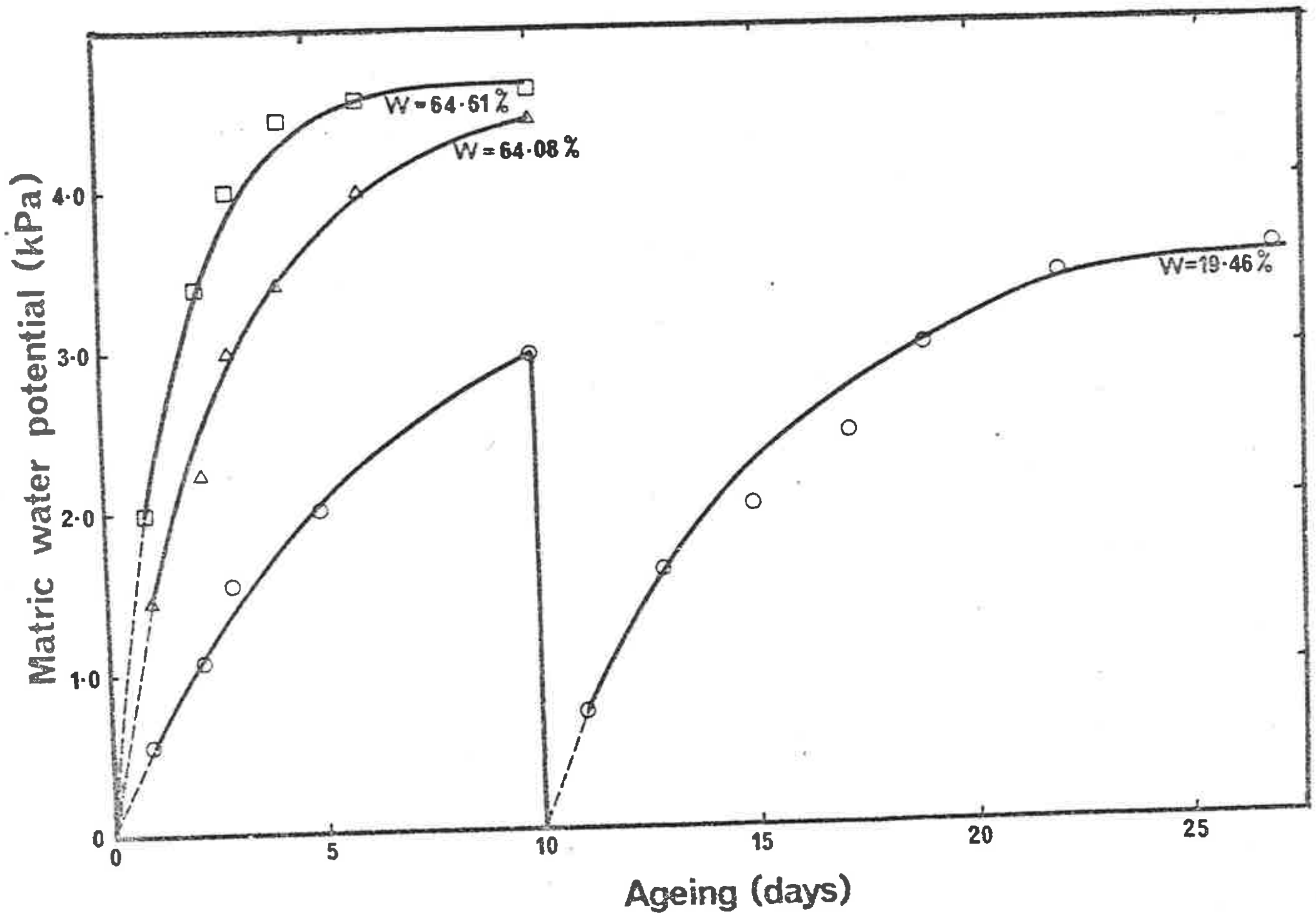


Fig. 3.4. Effect of ageing on matric water potential of Urrbrae (o), and Waco unsterilized (▫), and Waco sterilized (▴) soils.

matric water potential became more negative when the soil was sheared or remoulded. This difference can probably be explained by the conclusions of Cashen (1966) who studied thixotropic and dilatant behaviour. He found that in a thixotropic system, shearing made the matric water potential less negative, and in a dilatant system, on the other hand, shearing resulted in a more negative matric water potential. Thus the behaviour found in this experiment and that of Croney and Coleman (1954), Day and Ripple (1966) and Schweikle *et al.* (1974) should be thixotropy, and that of in the Bodman and Day (1943) and Campbell (1952) should be dilatancy. The effect of particle packing or void ratio on dilatant phenomenon has been discussed in Section 2.

To compare the increase in the strength at different water contents, the term "Thixotropic strength ratio", TSR, is used. TSR, was defined as the ratio of the strength of an aged sample to that of non-aged sample (Seed and Chan, 1957). The effect of water content at remoulding on TSR calculated from the result given in Table 3.3, is shown in Figure 3.5.

It is interesting to compare the effect of water content at remoulding on the TSR of the Strathalbyn and Waco soils on one hand, and that of the Urrbrae and Mortlock soils on the other hand. 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 a higher water content. Thus, the peak value of TSR occurred at water contents between the plastic and liquid limits. For the Urrbrae and Mortlock soils, however, the highest values of TSR were obtained at water contents just below and at 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

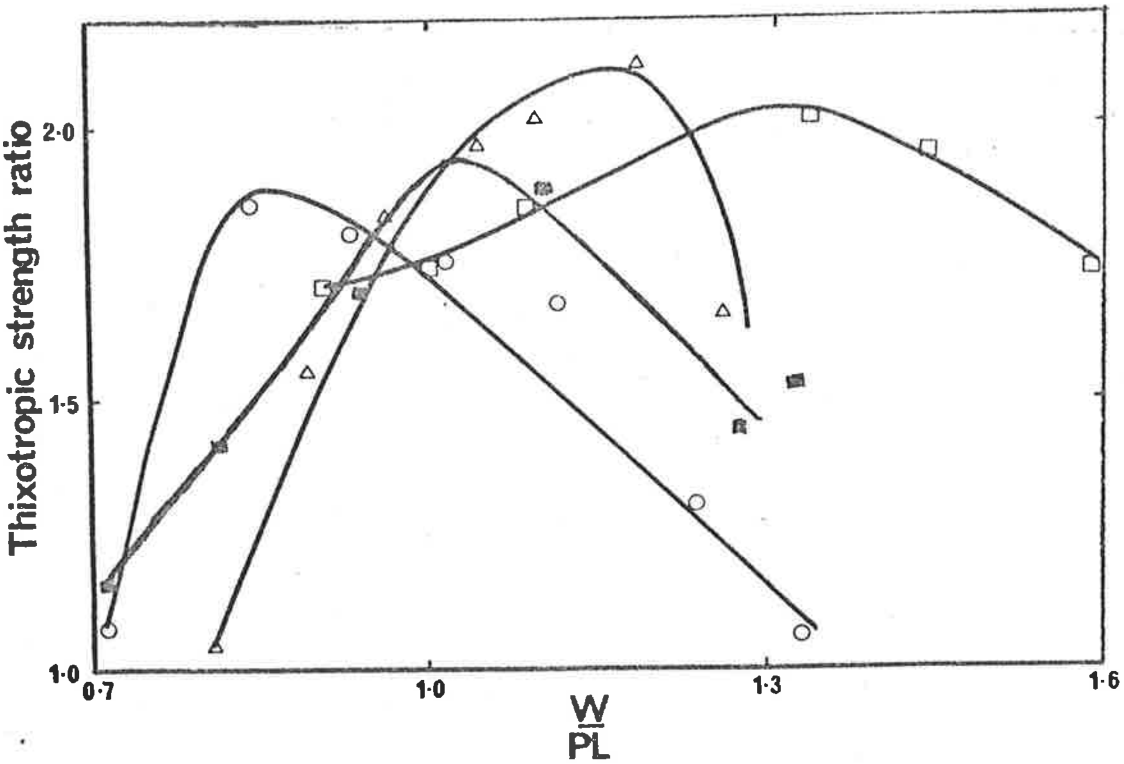


Fig. 3.5. Effect of water content ($\frac{W}{PL}$) on thixotropic strength ratio of Urrbrae (○), Strathalbyn (□), Mortlock (■) and Waco (▲) soils after 12 days of ageing.

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 thixotropic strength regain in compacted soil occurred also at water contents below the plastic limit. With a soil of 25% plastic limit and 39% liquid limit, he showed that at 21% 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%, and then decreased at higher water contents.

The results for the Strathalbyn and Waco soils were similar to that of Mitchell (1960). Mitchell's (1960) explanation, therefore, might be valid for these soils. It was suggested that at low water content the soil is strongly flocculated due to double layer water deficiency, and therefore thixotropic strength regain would be negligible. At high water content, 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 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 Figure 3.5, the highest values of TSR for the Urrbrae and Mortlock soils were obtained at water contents below the plastic limit and at about the plastic limit respectively. This is not unusual. Seed and Chan (1957), with a soil of 23% plastic limit and 37% liquid limit, found that thixotropic strength ratio increased with increasing water content from 15% to 18%, and then was about constant at water content 18% to 20%. Using the Vicksburg silty clay (26% plastic limit and 34% liquid limit), Gray and Kashmeery (1971) found that the maximum TSR occurred at about 22% water content.

The high strength regain at low water content for these soils can probably be explained in terms of the type of clay mineral present. As shown in Table 3.1 the clay minerals in these soils were illite and kaolinite. The Urrbrae data was obtained from Aylmore (1960), and the Mortlock soil was found by X-ray analysis. Cashen (1966) found that for kaolinite, thixotropic behaviour occurs at low water contents. 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 even decrease the strength as found by George (1967).

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

Samples from the A horizon of the Urrbrae soil were remoulded at 20%, 22% and 24% water content, and allowed to equilibrate overnight. These samples were again remoulded and aggregates of about 10 mm diameter were made by rolling 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 in a constant temperature room (20^{o}C).

In the second experiment, which was done for the aggregates made at 20% water content only, the aggregates were aged at -100 kPa (in pressure plates) and at -20 kPa and -1 kPa (on sintered funnels) also at 20^{o}C.

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

$$\sigma_T = 0.576\ F/d^2 \qquad (3.4)$$

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 ageing were not the same, and in both experiments the water contents at remoulding and at the measurement of strength were not the same. The term thixotropic hardening, therefore, is not really applicable. The more suitable term is "age hardening".

The results in Table 3.5 show that the tensile strength of remoulded aggregates increased with ageing. A significant increase in tensile strength occurred only at 20% and 22% water content (for the first experiment) and at -100 kPa and -20 kPa potential ageing (for the second experiment). This was in good agreement with the result given in Figure 3.5 which shows that the strength regain with ageing for the Urrbrae soil occurred mainly at low water content.

Pore Size distribution

It was shown in Figure 3.4 that ageing remoulded soils at constant water content resulted in a more negative value of matric water potential. Packing density, on the other hand, did not change appreciably with ageing (Table 3.3). These phenomena indicate that with ageing, there must be a change in pore size distribution rather than total porosity.

Table 3.5. 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	

Mean aggregate diameter = 13 mm.

To investigate this suggestion, an experiment on the effect of ageing on pore size distribution was carried out on the Strathalbyn and Mortlock soils. This was done by studying the changes in water characteristics of these two soils with ageing.

Samples from the A horizons of these soils were passed through a 1.0 mm sieve and remoulded at a water content slightly above the plastic limit, then left to equilibrate over night. At first, the soil was pressed into a plastic container as done before. However, it was very difficult to remove this sample (to obtain undisturbed sample) when intending to determine water content. To overcome this problem, the soil was rolled by hand to form soil balls of about 40 - 50 mm diameter. Some of these balls then wetted to -0.5 kPa potential in sintered funnels for a day, after which the balls were dried to the potential of -1, -3, -6, -10, -20, and -100 kPa for two days. Water content was determined gravimetrically, and these samples were considered to be the 0 day treatment. The remainder were stored individually in plastic containers, and then wrapped in thin plastic sheet and aluminium foil, and stored in a constant temperature room (20°C) for later testing. Four replicates were done for each level of matric potential for each period of ageing. This level of replication did not allow statistical tests for significance of observed differences to be done.

The results (Figures 3.6 and 3.7) show that ageing remoulded soils results in the disappearance of small soil pores and the creation of larger pores. This finding is consistent with the hypothesis of Schweikle *et al.* (1974). It has been suggested that when soil is remoulded, there is face-face arrangement of the clay particles in the matrix. In such a system, small pores are dominant. As the soil ages, the clay arrangement changes to edge-edge and/or edge-face orientation with a consequent loss of small pores and creation of larger pores.

The size of these pores can be calculated by the well known Jurin equation (Sills, Aylmore and Quirk, 1973)

$$P = \frac{-2\,T \cos \alpha}{\delta} \qquad (3.5)$$

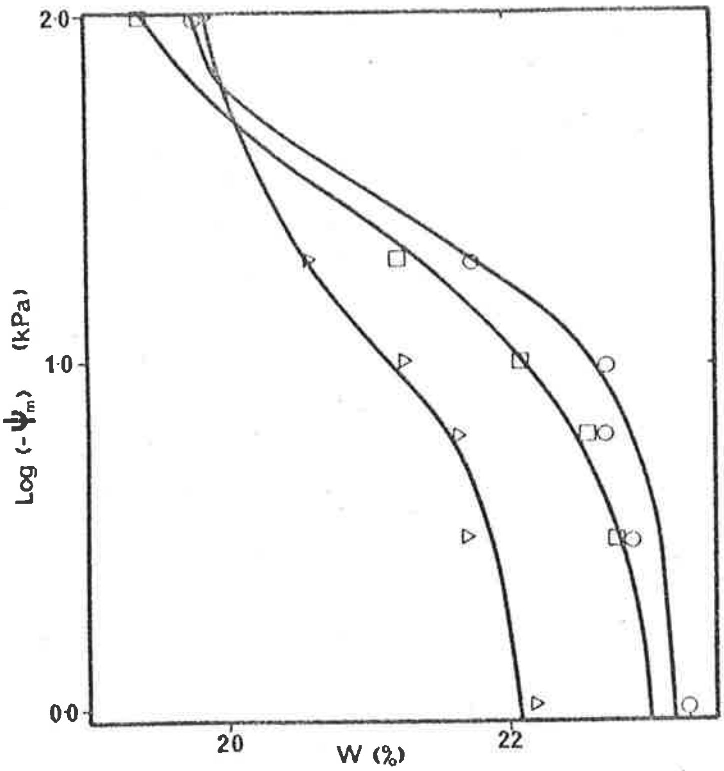
where, P is the applied pressure (here the water matric potential), T is the surface tension of water (72.75 mJm^{-2}), α is the contact angle of the water with the soil (here assumed to be zero), and δ is the particle separation or pore diameter.

To calculate pore size distribution, the gravimetric water content (W) was transformed into volumetric water content (θ) by

$$\theta = \rho_s W / \rho_w \qquad (3.6)$$

where ρ_s and ρ_w are the bulk densities of the soil and water respectively. The results are given in Figures 3.6b and 3.7b.

From Figure 3.7b, it can be seen that ageing the remoulded Strathalbyn soil for 3 days resulted in the disappearance of pores smaller than 2.8 μm, and in creation of pores larger than 2.8 μm. For the Mortlock



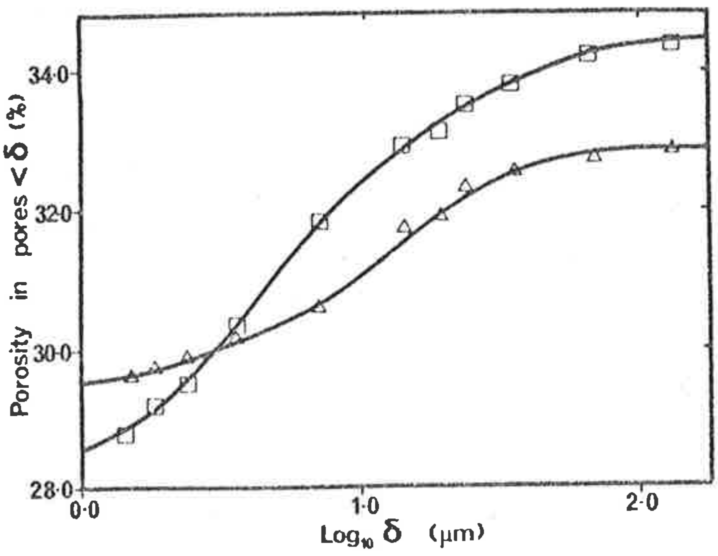
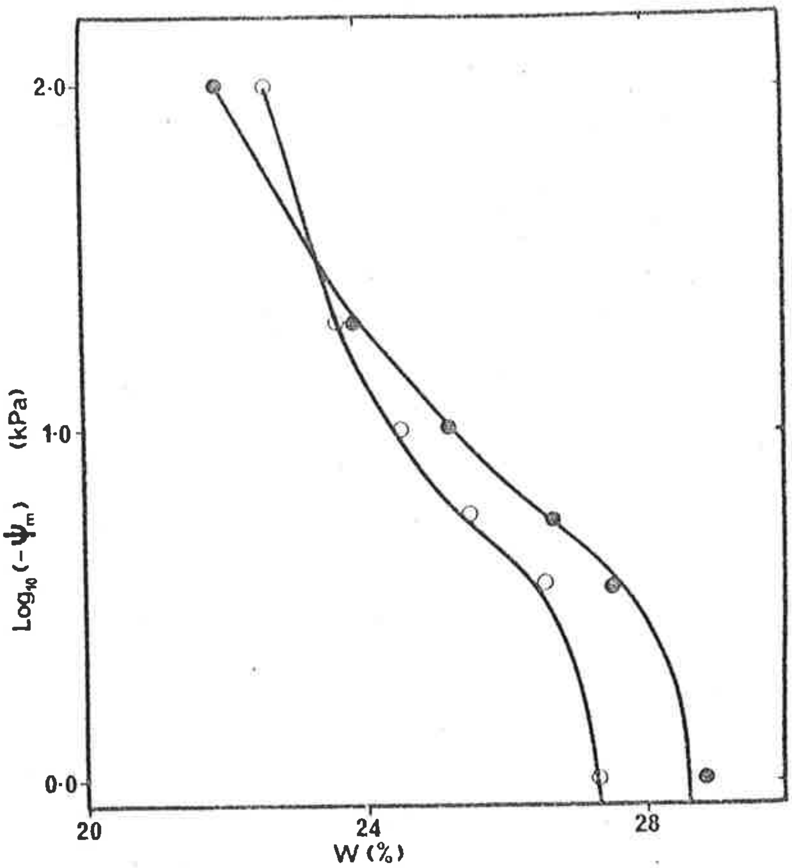


Fig. 3.6a. Effect of ageing on water characteristics of Strathalbyn soil.

△: 0 day; □: 3 days; ○: 6 days.

Fig. 3.6b. Effect of ageing on pore size distribution of Strathalbyn soil (ρ= 1.49).

△: 0 day; □: 3 days.



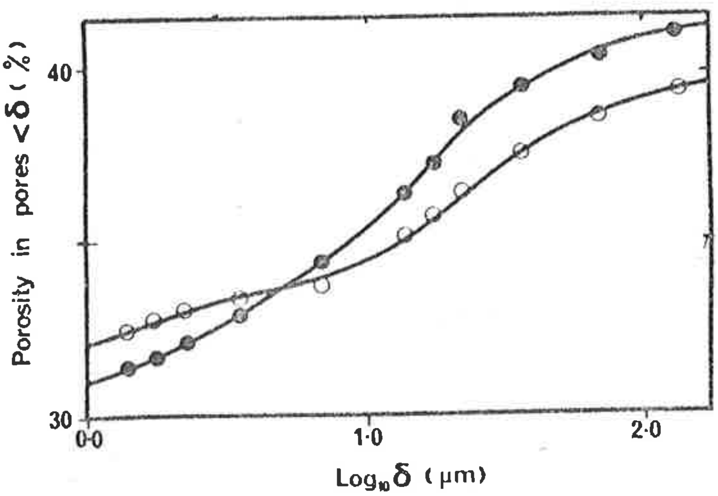


Fig. 3.7a. Effect of ageing on water characteristics of Mortlock soil.

o = 0 day; ● = 3 days.

Fig. 3.7b. Effect of ageing on pore size distribution of Mortlock soil (ρ = 1.44).

o = 0 day; ● = 3 days.

soil (Figure 3.7b) 3 days ageing resulted in the disappearance of pores smaller than 4.7 μm, and in the creation of pores larger than 4.7 μm.

Compression resistance

Little attention has been given to the effects of ageing on soil compressive strength. As discussed in section 2, this strength is defined as the ability of a soil to resist a volume change caused by applied stress. Hence this strength is of great interest to agricultural engineers, because it is a measure of the resistance of a soil to compaction damage. Berger and Gnaedinger (1949), with the Grand Forks and Crookstone clays, found that the compression behaviour of samples tested 6 months after remoulding was not different from that of the 0 day sample. Mitchell (1960), on the other hand, found that with the same applied stress, aged soil compresses less than the non-aged sample. This was shown by the fact that with the same applied stress, the void ratio of the 12 days aged sample was larger than that of the non-aged sample.

The effect of ageing on compression resistance was investigated on Urrbrae fine sandy loam. Soil from the A horizon was passed through 1 mm sieve, and then remoulded at 17% 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. 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 minutes 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 in a constant temperature room (20^{o}C). Two samples were prepared for each period of ageing.

Packing density was plotted against the applied stress, and this data was fitted to the equation

$$D_S = D_f - D_m \exp(-S/m) \qquad (3.7)$$

where D_S is the packing density at stress S, D_f is the final 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 3.6). The small value D_f indicates that with the same applied stress, the aged samples compress less than the non-aged samples. A large value of m indicates that the increase in packing density with increasing applied stress in aged samples occurred more slowly than in non-aged samples (Figrue 3.8). Thus ageing increases the resistance of the soil to compression.

Table 3.6. Values of D_f, D_m, and m parameters of equation (3.7) resulting from compression tests on remoulded Urrbrae soil aged for different times.

Ageing (days)	D_f	D_m	m (kPa)
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)

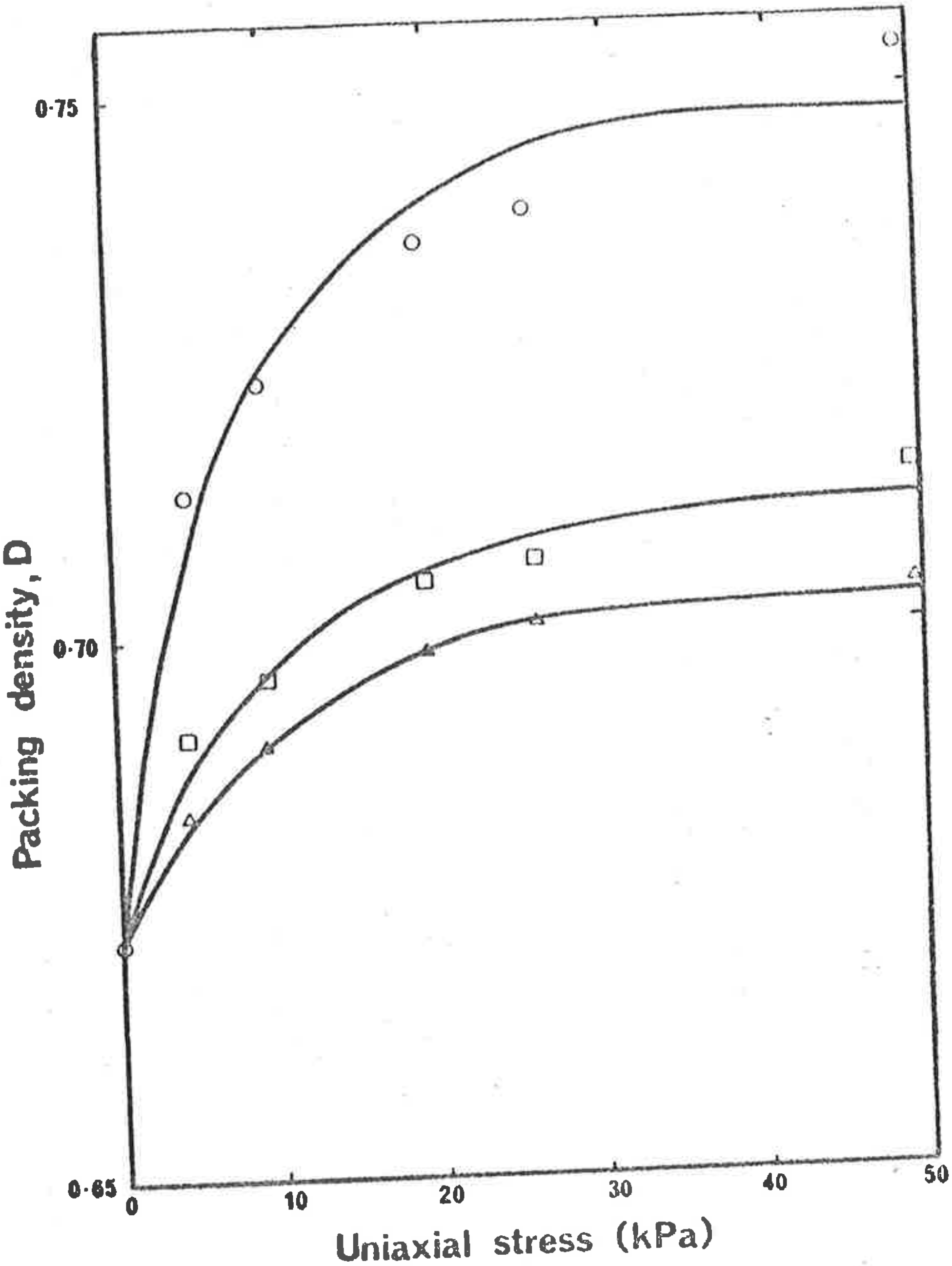


Fig. 3.8. Effect of ageing on the resistance of Urrbrae soil to compression. The continuous curves are fits of equation (3.7), and the measurements are given by: (○) 0 day; (□) 1 day; (△) 6 days.

As discussed in section 2, compression and shear failure have some common basis in that in both cases interparticle bonds have to be broken. Also, in shear and compression failure, the same particles must rearrange themselves. Since ageing increases shear strength, it is resonable that this results in an increase in the compression resistance.

3.2 Effect of chemical treatment on thixotropic behaviour

3.2.1 Introduction

When discussing the use of chemical soil conditioners, almost all agriculturists think about aggregate water stability. The references in this subject can be found elsewhere, these include the symposia held by the International Soil Science Society (SSSA, 1975; De Boodt and Gabriels, 1976; Emerson, Bond and Dexter, 1978). References on the effect of soil conditioners on soil mechanical properties, on the other hand, are very scarce. This subject, especially the effects of cement and lime on soil mechanical properties, has been mainly the interest of civil engineers.

Braunack and Dexter (1978) showed that the resistance to compression of beds of aggregates is a function of the tensile strengths of the individual aggregates. It was found that compression resistance increased with increasing aggregate tensile strength. Therefore, it is useful to consider the effects of soil conditioners on soil strength as well as on aggregate water stability. It will be more valuable if, besides increasing aggregate water stability, the soil conditioners used also increase or decrease (which ever is desired) the strength of the soil.

In the past, from the soil strength point of view, the use of soil conditioners has been usually related to crust strength (Jamison, 1954;

Allison and Moore, 1956; Pugh, Vomocil and Nielsen, 1960). To study this, these workers measured strength by the modulus of rupture test developed by Carnes (1934) and Richards (1953). They found that the modulus of rupture could be decreased by the application of soil conditioners.

Williams, Greenland and Quirk (1967) suggested that the modulus of rupture test did not normally reflect the strength of particle-polymer-particle bonds, but rather indicated that small stabilized aggregates were not easily remoulded to form a sample with the mechanical strength of the original stabilized material prior to crushing. This idea is consistent with thixotropic phenomenon discussed previously. Further Williams *et al.* (1967) hypothesized that soil conditioners, especially organic polymers, would in general tend to increase the strength of particle bonds in soils, and hence increase the bulk strength of the soil provided the adsorption of polymers takes place in such a way that the polymer molecules are able to form bonds between the majority of soil particles. This hypothesis is supported by their result which shows that the tensile strength of soil treated with poly (vinyl alcohol) or PVA is greater than that of untreated soil. An increase in the tensile strength of a soil treated with PVA and hydrous iron oxide has also been found by Dowdy (1975).

Ingles (1970) measured the unconfined compressive strength of chemically treated soil after it was aged for a year, and found that barium hydroxyde and calcium hydroxyde increased soil strength, whereas phosphoric acid and acetic acid decreased soil strength. Chisci, Lorenzi and Piccolo (1978) found a decrease in soil cohesion, measured using the Casagrande method, with the application of glotal (a mixture of ferric oxide and acid). Further, they found that the application of this conditioner also decreased the resistance of the field soil to probe penetration.

The object of the work described here was to study the effect of some chemical treatments on thixotropic behaviour and on soil strength. If there were different responses to different chemical treatments, then this phenomenon should be considered in determining the type of chemical used. In soils consisting of aggregates with low tensile strength, and thus a low compression resistance, it would be better if the chemicals used increased both aggregate water stability and aggregate tensile strength. In soils containing aggregates of high tensile strength, on the other hand, the chemical used should not increase the tensile strength, but just increase aggregate water stability. If necessary, conditioners which reduce aggregate strength could be used so that plant root elongation is not mechanically impeded.

3.2.2 Materials and Methods

Chemical treatment

The soil used was Urrbrae fine sandy loam, and the chemicals were orthophosphoric acid (H_3PO_4) and calcium sulphate ($CaSO_4.2H_2O$).

The phosphoric acid treatment was done by remoulding the soil samples with 0.1 M; 0.2 M; and 0.5 M phosphoric acid solution (35 ml/100 g soil), and then allowing them to rest and dry at ambient temperature for 6 weeks to allow the reaction to proceed and any soil aggregation to develop.

The calcium sulphate treatment was done by remoulding the soil with 35 ml $CaSO_4$ solution/100 g soil. The amount of $CaSO_4$ in the solution was such that it was equal to application rates of 1%, 2%, and 5% respectively. After allowing the reaction to take place for a week, the samples were leached with distilled water to remove any sodium in the solution. A flame test was done to test the existence of sodium in the leachate. As with the phosphoric acid treatment, the soils were allowed to rest and dry at ambient temperature for 6 weeks.

As a control, the Urrbrae fine sandy loam was remoulded with distilled water (35 ml/100 g soil), and then allowed to rest and dry at ambient temperature for 6 weeks.

Measurement of thixotropic hardening

Some soil from each treatment was passed through a 1 mm sieve, and then remoulded with distilled water at several water contents. These samples were allowed to equilibrate overnight, and then again remoulded and pressed in plastic containers of 42 mm diameter and 24 mm height.

The strengths of 2 - 3 cores at each water content for each treatment were measured immediately after sample preparation, and the rest were kept at constant water content for later testing. Soil strength was measured with the laboratory penetrometer described in section 3.1.

Measurement of aggregate tensile strength

Samples of the control and treated soils were passed through a 0.5 mm sieve, and then remoulded at 20%, 22% and 24% water content. After allowing the soils to equilibrate overnight, the soils were remoulded again, and aggregates of about 12 mm diameter were made by rolling this remoulded soil by hand.

Natural aggregates of > 9.5 mm, 6.7 - 9.5 mm, 4.0 - 6.7 mm, and 2.0 - 4.0 mm diameter were obtained by dry sieving of the control and treated soils. These aggregates were placed over saturated $CaCl_2$ solution in a vacuum desiccator for 3 weeks to give a matric water potential of -153 MPa.

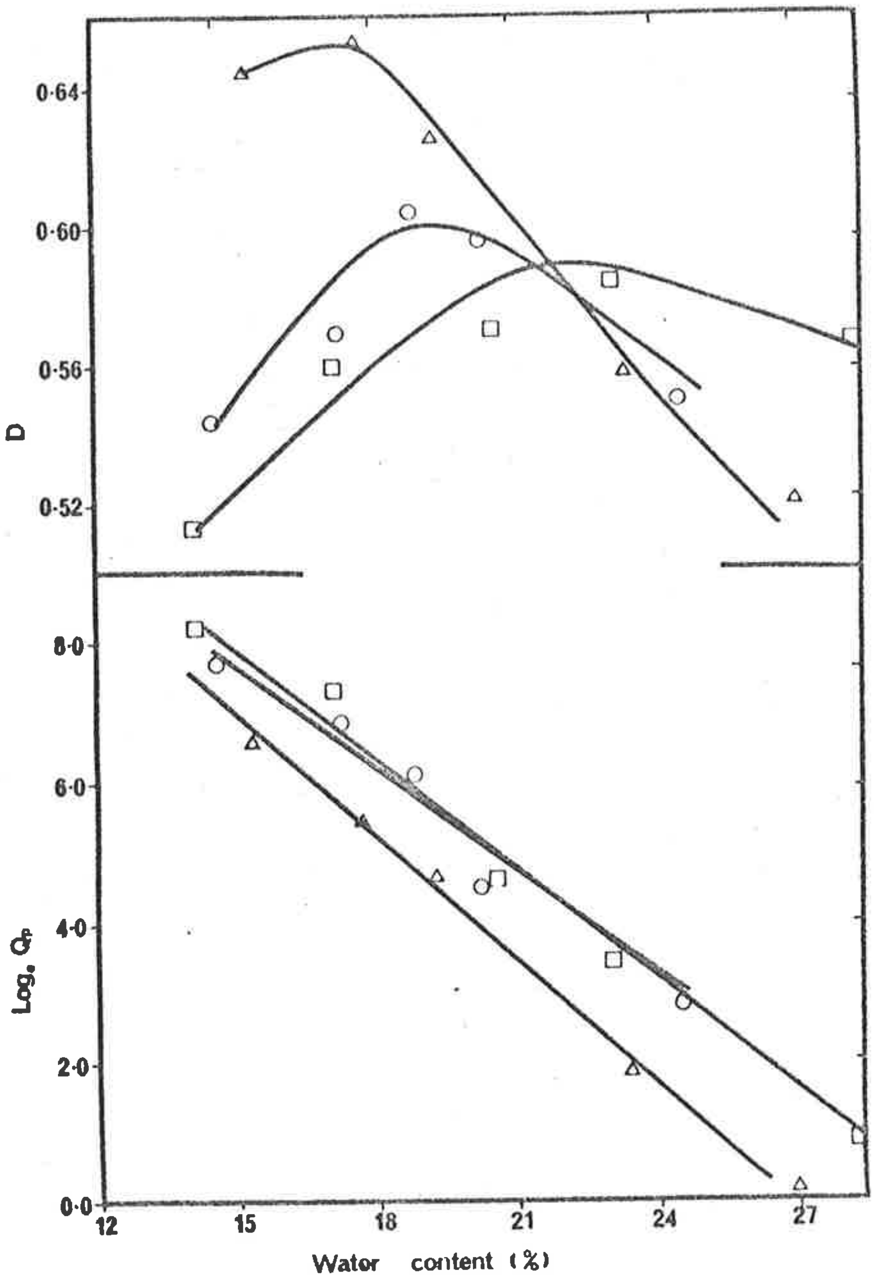


Fig. 3.9. Effect of chemical treatment on packing density (D) and penetration resistance (Q_p) of Urrbrae loam, as influenced by water content.

O: control; □ : 0.2 M H_3PO_4; △ : 2% $CaSO_4$

Tensile strength was determined by crushing the aggregates between flat parallel plates as described in section 3.1.

Compression resistance test

Bed of aggregates were made from 2.0 - 4.0 mm natural aggregates (after equilibrating them over saturated $CaCl_2$ solution) in a standard consolidometer cell. The compression test was done with a standard consolidometer with uniaxial stresses of 0; 9.8; 19.6; 29.4; 39.2; 52.2 and 66.1 kPa respectively; as described in section 3.1.

3.2.3 Results and Discussion

Thixotropic hardening

Effects of phosphoric acid and calcium sulphate application on packing density and on the resistance of the soil to probe penetration are shown in Figure 3.9. At low water content, phosphoric acid decreased packing density, whereas calcium sulphate increased packing density. At high water content, on the other hand, the opposite effect occurred.

Figure 3.7 also shows that the increase in packing density due to calcium sulphate application is not followed by an increase in the penetration resistance, but even decreases the penetration resistance. The addition of phosphoric acid, on the other hand, although decreasing packing density, results in an increase in the resistance of the soil to probe penetration. The increase in penetration resistance disappears at high water content ($W > 25\%$).

The variation in penetration resistance with water content both for the treated and control soils was fitted to equation (3.3). By replacing the ratio of water content to the plastic limit, $\frac{W}{PL}$, with water content, W, equation (3.3) becomes

$$\log_e Q_p = B - b\,W \qquad (3.8)$$

where B and b are adjustable parameters.

The resulting values of B and b parameters, together with the penetration resistance at water content of 12%, Q_p 12, and of 20%, Q_p 20, as references are given in Table 3.7.

Table 3.7. Values of B and b parameters of equation (3.8), and the strengths at 12 and 20% water contents, Q_p 12 and Q_p 20, of remoulded Urrbrae soil as influenced by chemical treatments.

Treatment	B	b	r^2	Q_p12 (MPa)	Q_p20 (kPa)
Control	15.14	0.50	0.98	9.40	172.8
0.2M H_3PO_4	15.45	0.51	0.98	10.84	178.5
2% $CaSO_4$	15.57	0.58	0.99	5.63	55.5

It can be seen (Table 3.7) that the penetration resistance of phosphoric acid treated soil at 12% water content is greater than that of the control soil (10.8 MPa compared to 9.4 MPa). At about 20% water content, however, the penetration resistance of phsophoric acid treated soil is about the same as that of the control soil. The penetration resistance of calcium treated soil is lower than that of the control and the phosphoric acid treated soil.

The effect of ageing on the penetration resistance of the control and chemically treated soil is given in Table 3.8. It was observed that the penetration resistance of the remoulded aged sample of the calcium sulphate treated soil, especially at low water content ($W < 19\%$) was

Table 3.8. Effect of ageing on the penetration resistance of remoulded Urrbrae soil as influenced by chemical treatments.

Ageing (days)	0			6		
Treatment	Q_p (kPa)	Water content (%)	Packing density	Q_p (kPa)	Water content (%)	Packing density
Control	2353.4	14.50	0.538	2519.3	14.25	0.544
	1009.9	17.0	0.575	1711.5	16.98	0.569
	417.4	18.68	0.600	774.4	18.26	0.608
	110.8	20.04	0.592	168.4	20.14	0.597
	19.3	24.54	0.550	22.0	24.01	0.546
H_3PO_4 (0.2M)	3193.5	13.70	0.516	3278.0	13.72	0.515
	1601.6	17.06	0.564	2934.6	17.07	0.560
	117.6	20.54	0.570	326.2	20.51	0.570
	30.4	22.90	0.584	100.6	22.87	0.583
	2.6	28.40	0.544	5.9	28.32	0.570
$CaSO_4$ (2%)	746.9	15.30	0.645	1473.0	15.36	0.648
	228.6	17.68	0.660	497.1	17.66	0.655
	107.0	19.28	0.625	224.4	19.21	0.626
	6.2	23.24	0.560	16.5	23.25	0.559
	1.1	27.00	0.514	5.8	27.05	0.520

greater than that of the 0 day sample. It is thought that the remoulding forces used were not high enough to destroy the bonds formed by calcium sulphate at this water content. Because of this, in the following discussion, the term age hardening will be used.

A plot of water content at time of remoulding against age hardening ratio, shows that both phosphoric acid and calcium sulphate addition increase the age strength ratio (Figure 3.10). For the phosphoric acid

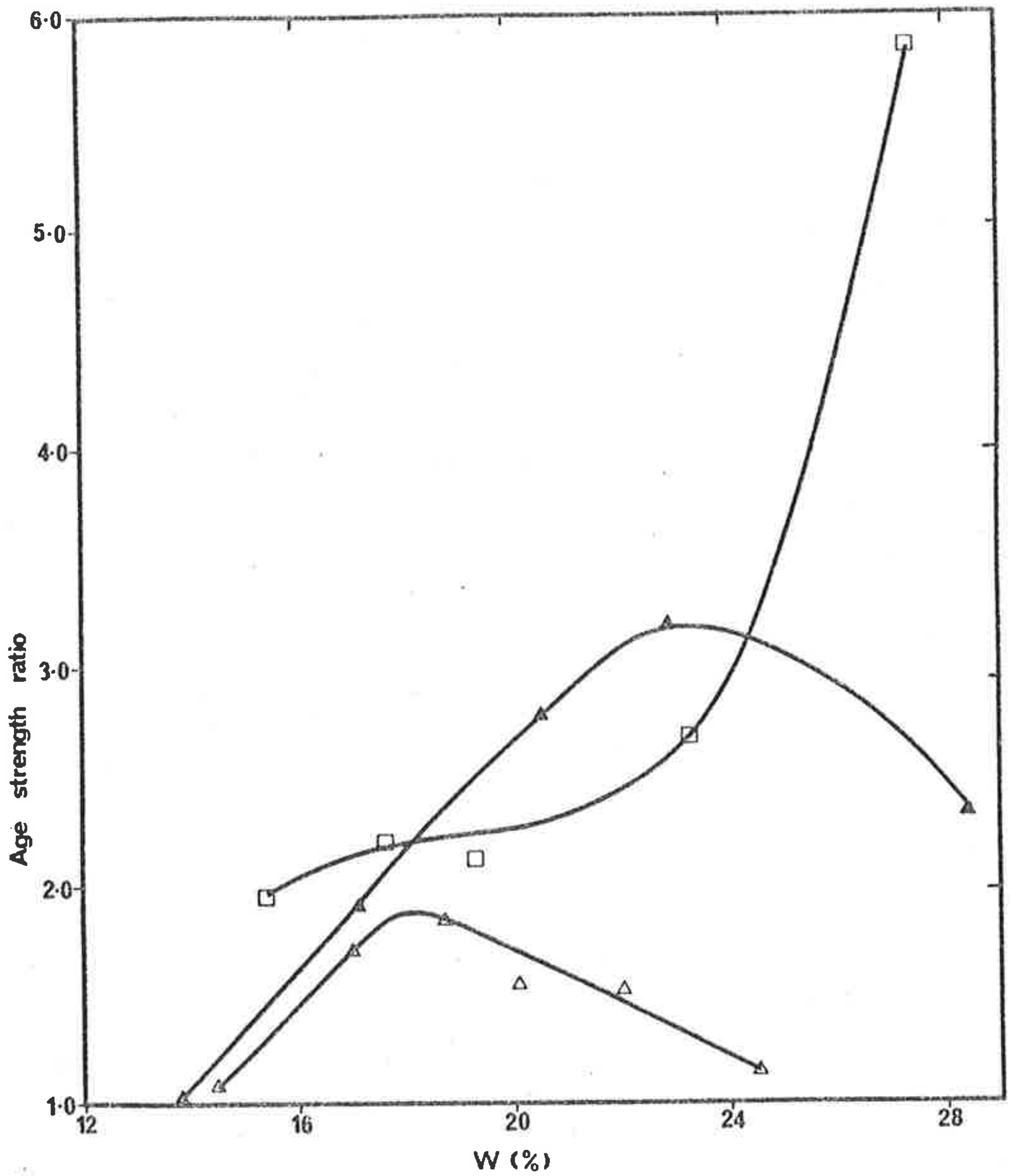


Fig. 3.10. Effect of chemical treatment on age strength ratio of Urrbrae loam after 6 days of ageing, as influenced by water content.

○: control; ●: 0.2 M H_3PO_4; □ : 2% $CaSO_4$

treated soil, age strength ratio increases with increasing water content up to 23% water content, and then decreases with further increases in water content. For the calcium treated soil, on the other hand, age strength ratio still increases with increasing water content up to W=28%.

The increase in age strength ratio with chemical treatment is thought to be a consequence of the formation of chemical compounds which act as cementing bonds, such as carbonate, iron or aluminium oxide. Ingles (1970) has suggested that calcium which is always present in the extract as calcium hydroxide can form cementing bonds. Yeoh (1979) has found that phosphoric acid addition releases aluminium and silicon.

Seed *et al.* (1960) showed that soil sensitivity increased linearly with increasing amounts of carbonates plus free iron oxide in soils. This indicates that age strength should increase with increasing concentration of cementing bonds present in the soil. An increase in sensitivity with some other chemical additives, such as phosphate, has been noted by Rosenqvist (1955).

Aggregate tensile strength

The effect of chemical treatment on the tensile strength of freshly remoulded (0 day) and 6 days aged aggregates is shown in Figure 3.11. Unlike the penetration resistance, calcium sulphate application increased the tensile strength of both the freshly remoulded and 6 days aged aggregates. Phosphoric acid application, on the other hand, decreased the tensile strength of these aggregates.

Further, Figure 3.11 shows that the greatest age hardening for the phosphoric acid treated soil was obtained at about 24% water content. This result is in agreement with the result given in Figure 3.10.

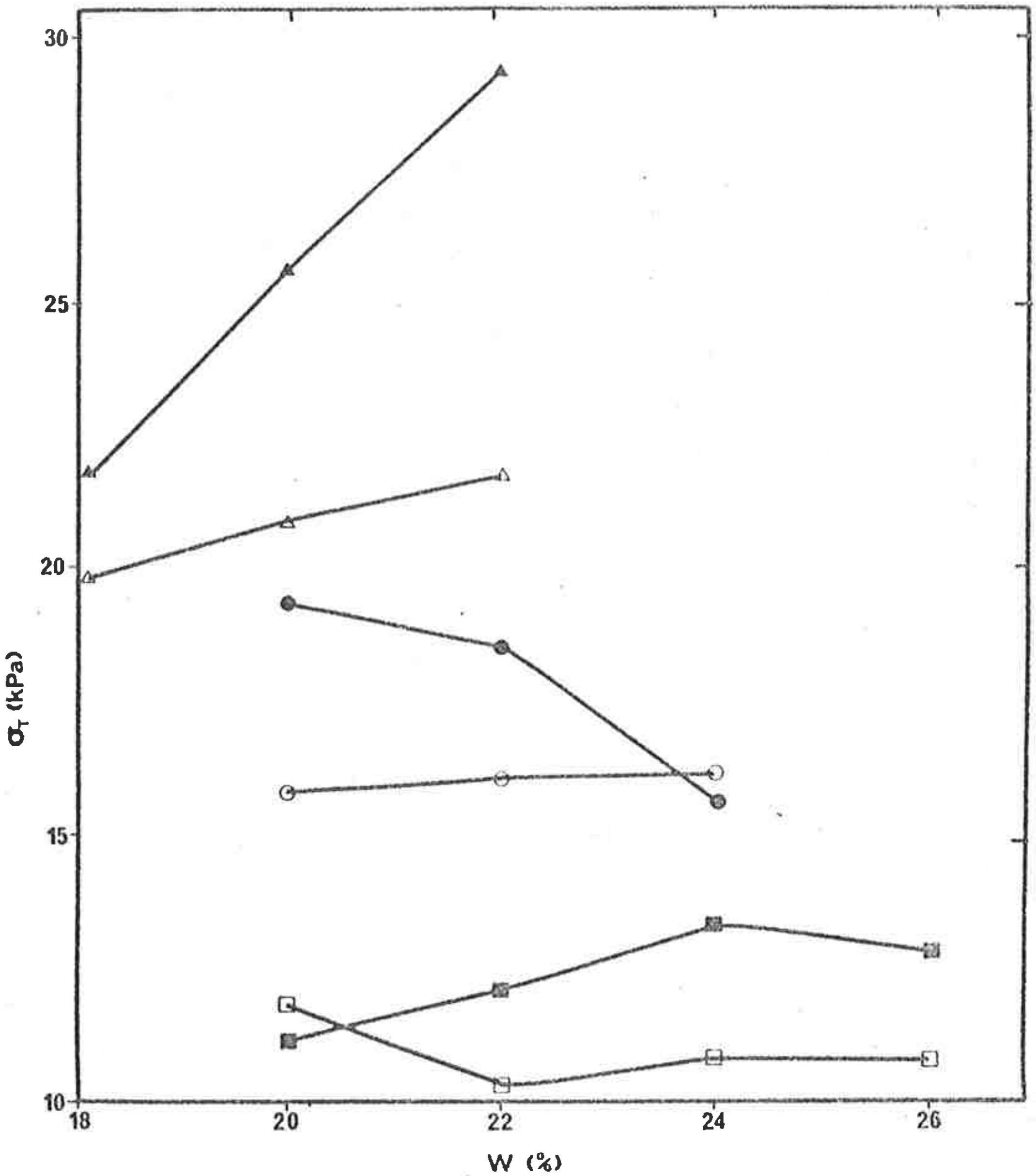


Fig. 3.11. Effect of ageing on the tensile strength of remoulded chemically treated Urrbrae loam, as influenced by water content.

○: control (0 day); ●: control (6 days);
□: 0.5 M H_3PO_4 (0 day); ■ 0.5 M H_3PO_4 (6 days);
△: 5% $CaSO_4$ (0 day); ▲: 5% $CaSO_4$ (6 days).

The 5% $CaSO_4$ treated soil liquified when it was remoulded at water contents above 22%. This prevented aggregates being prepared. Thus, $CaSO_4$ decreased the strength and increased the sensitivity of remoulded soil. This is discussed further on p.95-96.

The decrease in aggregate tensile strength due to phosphoric acid addition and the increase in aggregate tensile strength with calcium sulphate addition was found also in the natural aggregates (aggregate formation occurred as described in section 3.2.2). For these aggregates, the decrease in tensile strength occurs with increasing phosphoric acid addition up to at least 0.5 M concentration. The tensile strength of aggregates treated with calcium sulphate increased up to 2% calcium sulphate application, and then decreased with increasing application rate (Figure 3.12).

One could argue that the application rate of calcium sulphate in this experiment was rather high. 1% of calcium sulphate is equal to about 14 tonnes $CaSO_4$/ha (assuming a soil bulk density of 1.4 g/cm^3, and the chemical is mixed into the top 10 cm). A common application rate of calcium sulphate in agricultural practice is around 7.5 tonnes $CaSO_4$/ha (Loveday, 1974). With this rate, Loveday (1974) found that calcium sulphate decreased the penetration resistance of the soil.

A decrease in tensile strength of remoulded soil due to phosphoric acid application has also been found by Lutz and Pinto (1965) and Yeoh (1979). Ingles (1970) found that even after ageing for 90 days, the unconfined compressive strength of phosphoric acid treated soil was still less than that of the control. For this phenomenon, Ingles (1970) explained that phosphoric acid was incapable of forming insoluble compounds to provide bonds, so that the strength did not increase. He, however, gave no explanation for the strength decrease.

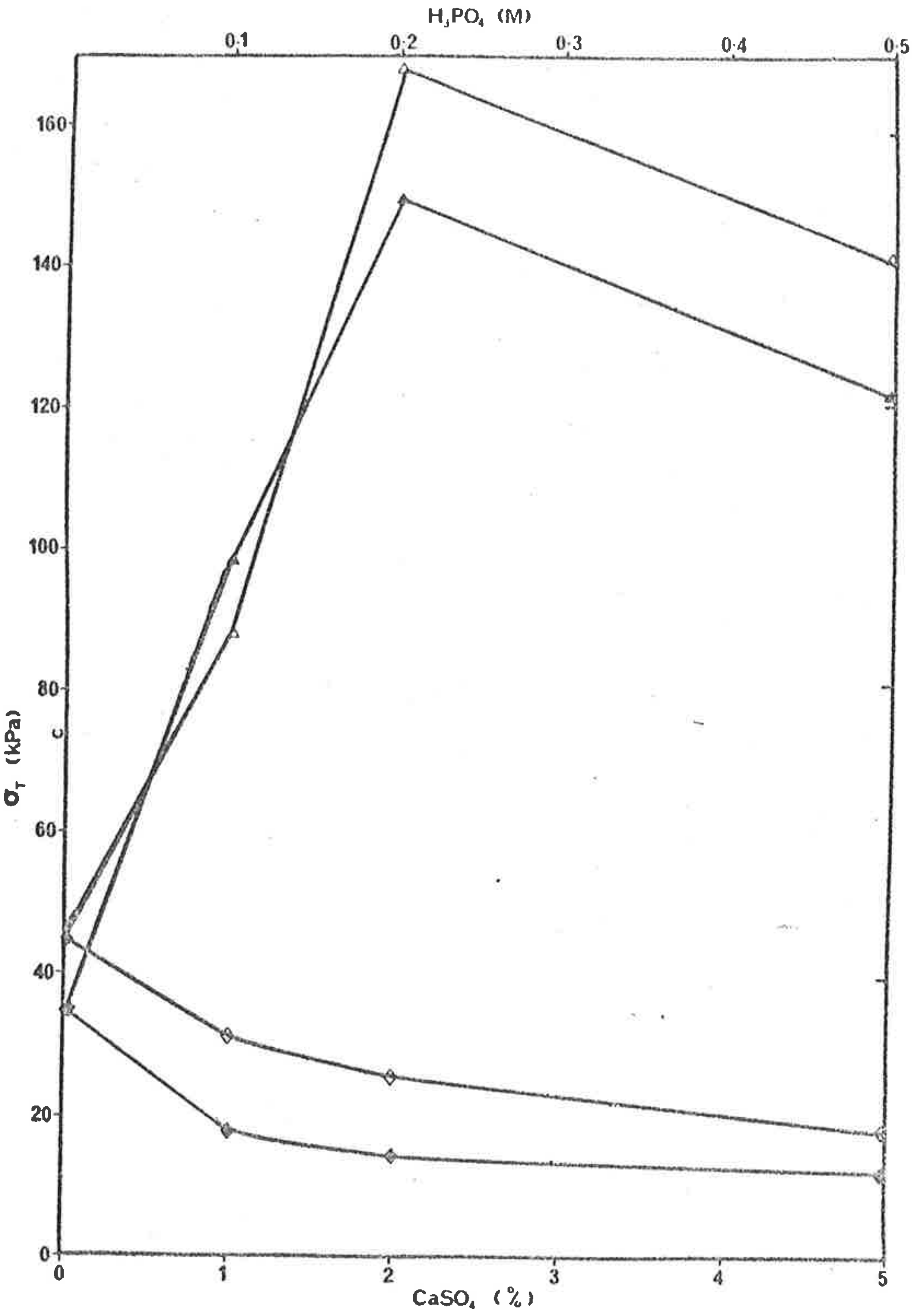


Fig. 3.12. Effect of chemical treatment on the tensile strength (σ_T) of natural aggregates of Urrbrae loam.

◇: H_3PO_4 (2 - 4 mm)

◆: H_3PO_4 (9.5 - 17 mm)

△: $CaSO_4$ (2 - 4 mm)

▲: $CaSO_4$ (9.5 - 17 mm)

A comparison of the results given in Figure 3.9 with those in Figures 3.11 and 3.12 leads to an explanation of the action of phosphoric acid on soil. As discussed in section 2, the resistance offered by soil to a penetrometer probe is a compound of shear and compressive strength, and soil probe friction. Aluminium and silicon which are released by phosphoric acid (Yeoh, 1979) hold clay size particle to form larger units or volume elements which are separated by micro-cracks or flaws. A penetrometer imposes a strain pattern in the soil (Figure 2.6, Section 2) which cannot take advantage of these flaws, and hence the penetrometer resistance increases. Also, the increased effective particle size can increase the angle of soil internal friction (Kenney, 1967), and thus give rise to an increase in soil shear strength through this mechanism.

This suggestion is supported by the fact that at high water content, the penetration resistance of the phosphoric acid treated soil was about the same as that of the control. Mulqueen *et al.* (1977) found that as water content increases, penetration resistance becomes insensitive to shear or compressive strength changes. In addition, since water acts as a lubricant when it is applied to sheet minerals (Horn and Deere, 1962), the difference in the frictional resistance at high water content disappeared so that the penetration resistance of these two soils were not much different as was found in this experiment.

To test the truth of the above suggestion, the shear strength parameters of these treated soils were determined. Soil samples were passed through a 0.5 mm sieve, and remoulded at 17% water content. After equilibration overnight, they were remoulded again, and cores with 38 mm diameter and 82 mm height were made. Shear tests (drained) were done in tri-axial cell with a constant strain rate of 0.4 mm per minute, and with minor principal stresses of σ_3 = 0; 100; and 200 kPa respectively.

Plate 3.3. Measurement of soil shear strength in a triaxial cell.

It was observed that the phosphoric acid treated soil (freshly remoulded and 4 days aged) tested at the minor principal stress $\sigma_3 = 0$ kPa, produced a clear failure plane. For the others, until 10% strain, even in some observation where the measurement was continued until 20% strain, did not produce a failure plane (Plate 3.4). For samples which produced failure planes, the strength was measured as the peak strength, and for those which did not produce failure planes, the strength was measured at 10% strain.

The results are shown by Mohr circles (Figure 3.13). It can be seen that the friction angle of the phosphoric acid treated soil ($28^{o}.8'$) was much higher compared to that of the control ($16^{o}.9'$) and the calcium sulphate treated soil (16^{o}).

The shear strength of these soils increased with ageing (Figure 3.14). The shear strengths of the control, phosphoric acid treated, and calcium sulphate treated soils are

$$\tau_f = 32 + \sigma \tan 16^{o}.9' \qquad (3.9a)$$

$$\tau_f = 22 + \sigma \tan 28^{o}.8' \qquad (3.9b)$$

$$\tau_f = 46 + \sigma \tan 16^{o} \qquad (3.9c)$$

at 0 day, and

$$\tau_f = 40 + \sigma \tan 18^{o}.3' \qquad (3.10a)$$

$$\tau_f = 40 + \sigma \tan 29^{o}.3' \qquad (3.10b)$$

$$\tau_f = 55 + \sigma \tan 17^{o}.5' \qquad (3.10c)$$

after ageing for 4 days, respectively.

The suggestion and findings discussed above is not necessarily in contradiction with the explanation given by Yeoh (1979) who used the particle size distribution changes as the basis of his explanation. He observed that phosphoric acid application increased the proportion of silt and sand size particles. He, therefore, suggested that phosphoric

Plate 3.4. Soil deformations resulting from triaxial tests after ageing for 4 days.

a. Control (10% strain, σ_3 = 0 kPa)

b. 0.5 M H_3PO_4 treated (10% strain, σ_3 = 0 kPa)

c. 1% $CaSO_4$ treated (20% strain, σ_3 = 0 kPa)

a b

c

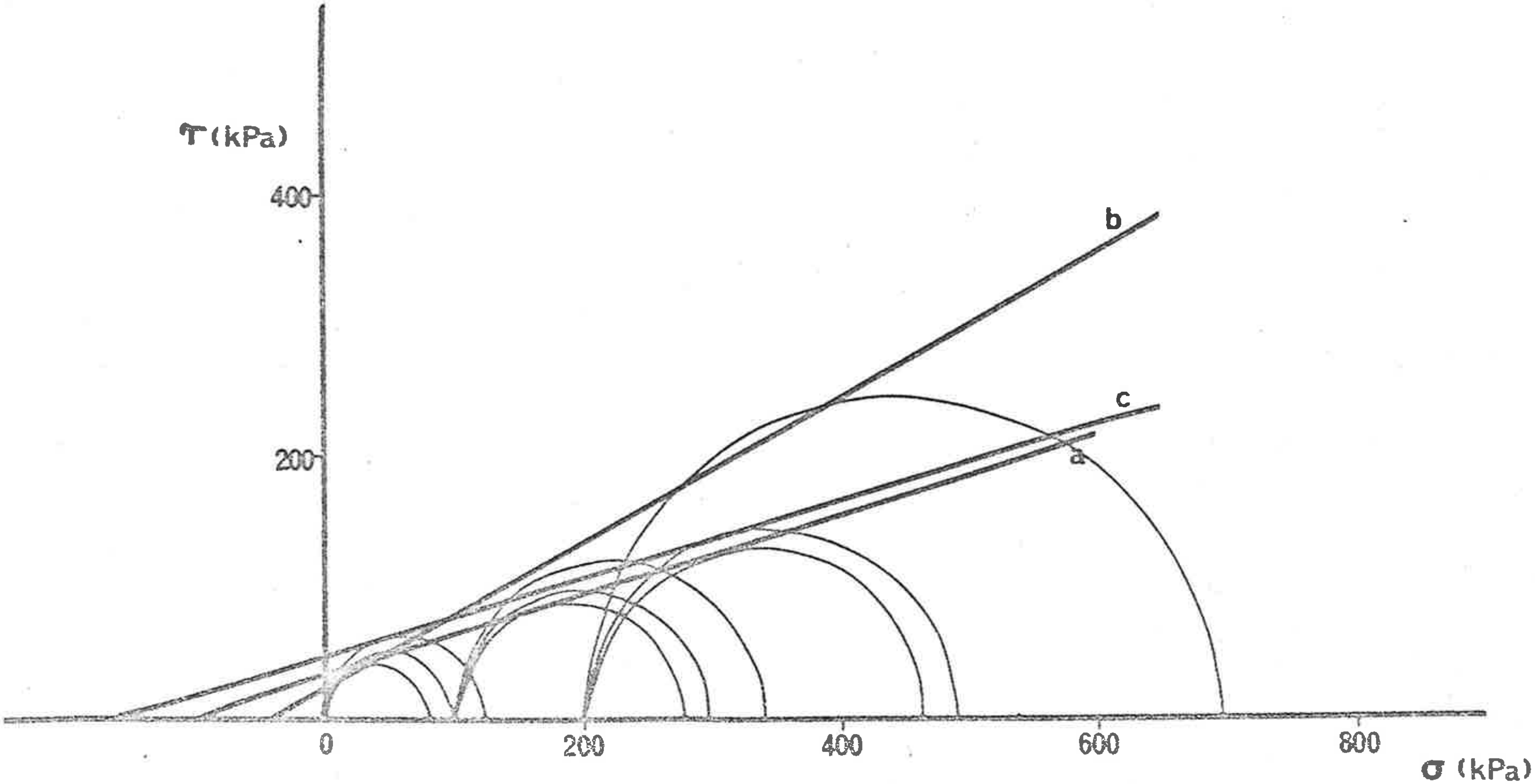


Fig. 3.13. Mohr failure envelope of the control (a), phosphoric acid treated (b), and calcium sulphate treated (c) of Urrbrae loam at 0 day aged.

Control	$\tan\phi = 0.30 \rightarrow \phi = 16^{\circ}.9'$		$\tau_f = 32 + \sigma \tan 16^{\circ}.9'$
Phosphoric acid	$\tan\phi = 0.55 \rightarrow \phi = 28^{\circ}.8'$		$\tau_f = 22 + \sigma \tan 28^{\circ}.8'$
Calcium sulphate:	$\tan\phi = 0.29 \rightarrow \phi = 16^{\circ}.0'$		$\tau_f = 46 + \sigma \tan 16^{\circ}.0'$

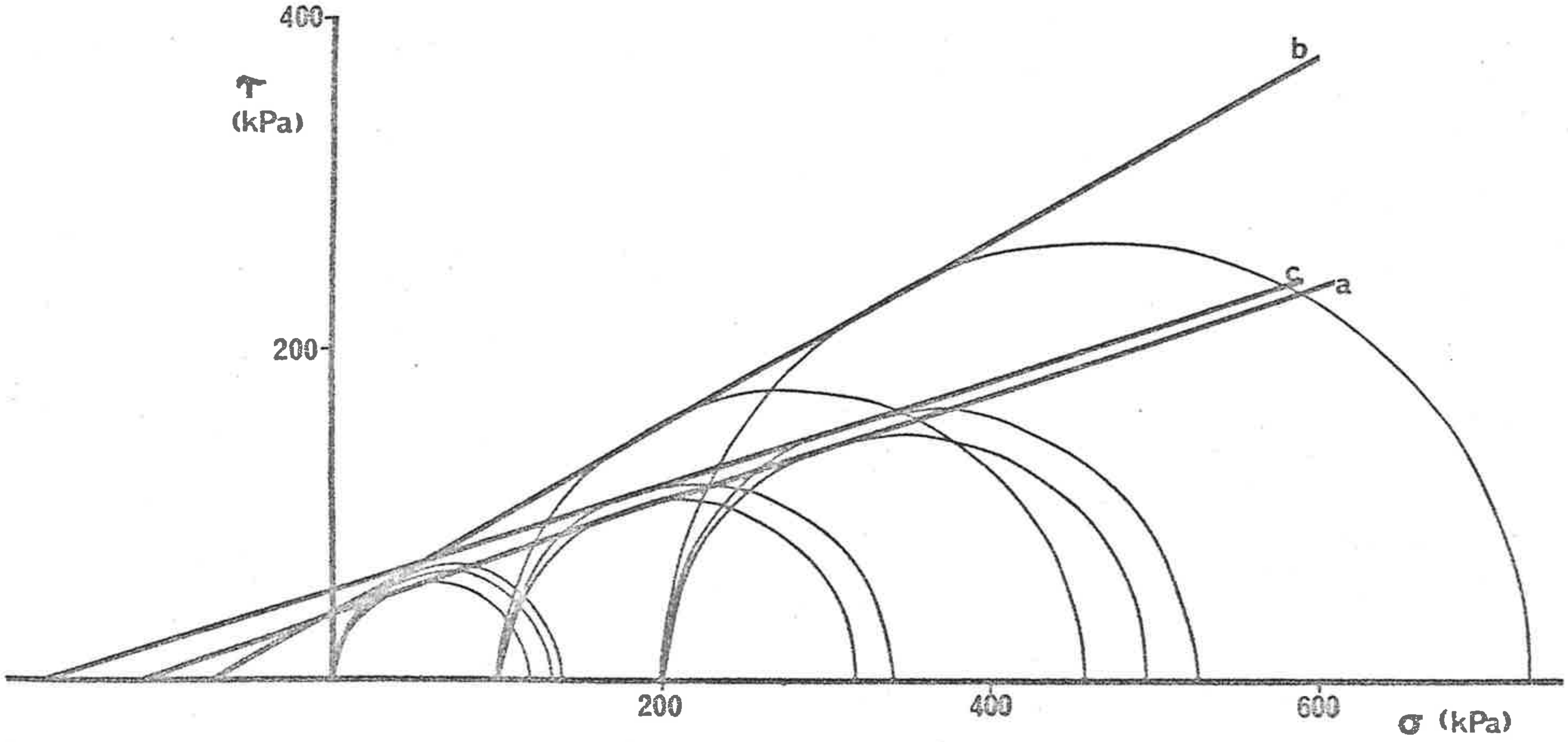


Fig. 3.14. Mohr failure envelope of the control (a), phosphoric acid treated (b) and calcium sulphate treated (c) of Urrbrae loam at 4 days aged.

Control : $\tan \phi = 0.33 \rightarrow \phi = 18^{o}.3'$ $\tau_f = 40 + \sigma \tan 18^{o}.3'$

Phosphoric acid : $\tan \phi = 0.56 \rightarrow \phi = 29^{o}.3'$ $\tau_f = 40 + \sigma \tan 29^{o}.3'$

Calcium sulphate: $\tan \phi = 0.32 \rightarrow \phi = 17^{o}.5'$ $\tau_f = 55 + \sigma \tan 17^{o}.5'$

acid addition would decrease the actual contact between soil particles, and hence resulted in a decrease in attractive forces with a consequent reduction of the tensile strength.

To study the effect of treatment on particle size distribution, the samples were dispersed with 5% sodium hexametaphosphate, and the size distribution was measured by the hydrometer method. The result (Table 3.9) shows that phosphoric acid application increased the proportion of sand size particles and decreased clay size particles. This phenomenon can be explained from the finding of Yeoh (1979) that phosphoric acid releases aluminium and silicon which may bind clay particles into larger units.

Teble 3.9. Effect of phosphoric acid and calcium sulphate application on particle size distribution of Urrbrae loam.

Fraction (USDA system)	% in soil treated with control	0.2M H_3PO_4	2% $CaSO_4$
clay size (< 2 μm)	15.5	7.5	17
silt size (2 - 50 μm)	60.5	59.0	57
sand size (> 50 μm)	24.0	33.5	26

For calcium sulphate treatment, Ingles (1970) suggested that calcium which is always present in extracts migrates to and reacts at the silica- or aluminium-rich surface (i.e. the clay) to coat it with an insoluble product. This leads to an increase in the strength of the soil.

The lower penetration resistance of the soil treated with calcium sulphate (Figure 3.9) did not necessary mean that calcium sulphate application decreased soil strength. This was the strength of remoulded soil, and probably just indicates that the addition of calcium sulphate would increase the sensitivity of the soil as discussed previously. When this soil is allowed to age for a longer time, its penetration resistance should be higher than the untreated soil. This suggestion is supported by the result given in Figure 3.15. It can be seen that after 16 days ageing, the strength regain of the control soil effectively ceased. For the calcium treated soil, on the other hand, the strength regain still

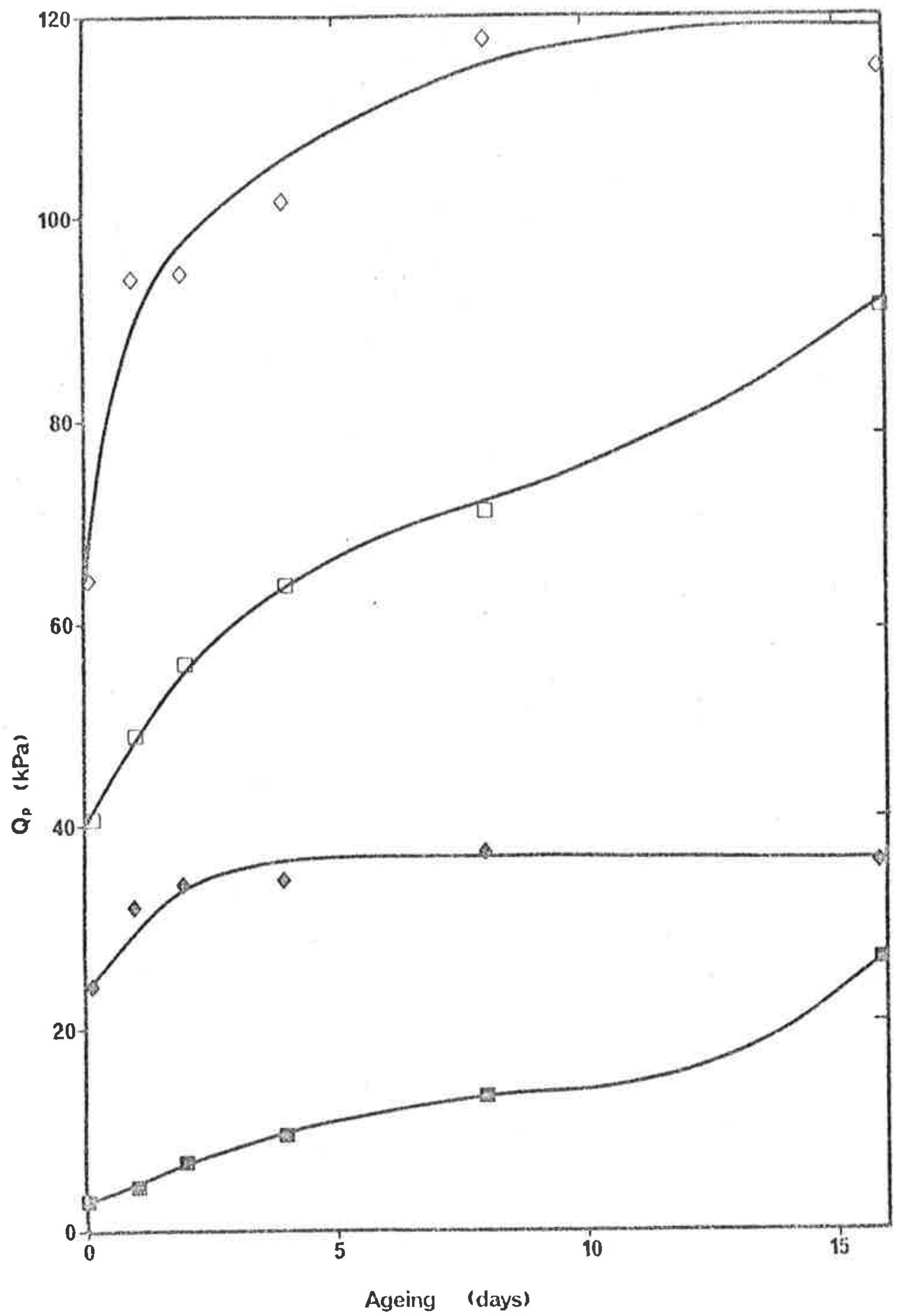


Fig. 3.15. Effect of ageing on the resistance to probe penetration of $CaSO_4$ treated Urrbrae loam.

◇ : Control (W = 19.08)

◆ : Control (W = 22.40)

□ : 5% $CaSO_4$ (W = 19.43)

■ : 5% $CaSO_4$ (W = 22.06)

increased steadily. Extrapolation to greater ageing times is rather hazardous, but is seems probable that the penetration resistance of $CaSO_4$ treated soil may be greater than that of the control. This result supports the suggestion of Williams *et al.* (1967) discussed previously. Ingles (1970) found that the unconfined compressive strength of calcium hydroxide treated kaolinite (7 days aged) was about 2.2 MPa, and after ageing for one year the strength was about 12.8 MPa. The strength of the control treatment was about 1.1 MPa.

Plotting the logarithm of the tensile strength as ordinate and the logarithm of the volume of natural aggregates (see 3.2.2) as abscissa resulted in a straight line

$$\log_e \sigma_T = K - k \log_e V \qquad (3.11)$$

Here, K and k are adjustable parameters depending on the properties of the soil.

The resulting K and k value is given in Table 3.10, and the resulting curves in Figure 3.16. As a reference, the tensile strength of 10 mm aggregates, S_{10}, is also given in Table 3.9.

Table 3.10. Values of K and k parameters of equation (3.11) of Urrbrae loam as influenced by chemical treatments.

Treatment	K	k	r^2	S_{10} (kPa)
control	2.42	0.08	0.86	35.1
0.1 M H_3PO_4	0.63	0.16	0.95	19.8
0.2 M H_3PO_4	0.27	0.18	0.93	16.4
0.5 M H_3PO_4	0.86	0.12	0.92	13.3
1% $CaSO_4$	4.90	-0.02	0.62	95.5
2% $CaSo_4$	4.53	0.04	0.68	157.5
5% $CaSO_4$	4.43	0.03	0.68	123.9

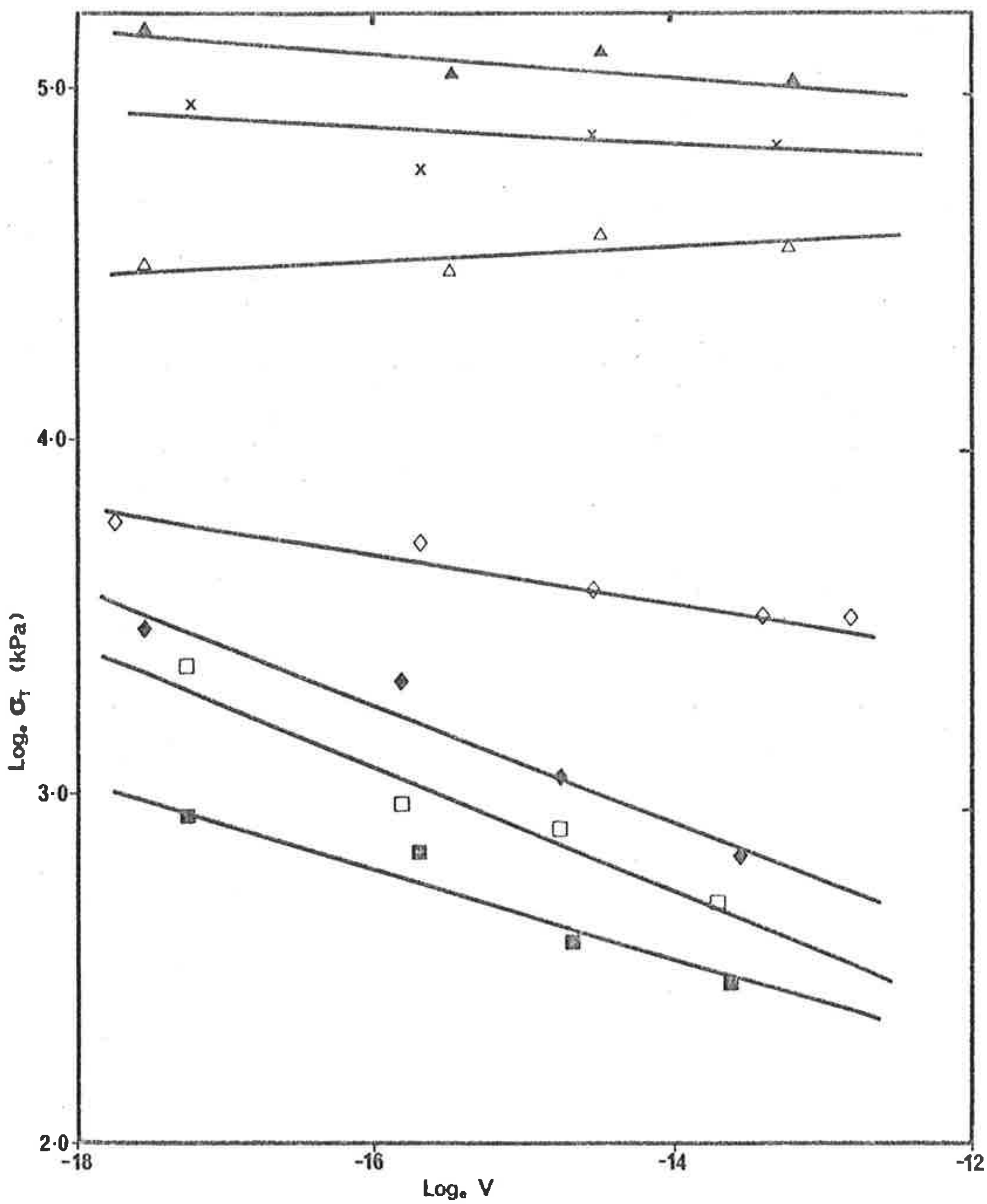


Fig. 3.16. Effect of chemical treatment on the log aggregate tensile strength-volume relationship of Urrbrae loam. The continuous curves are fit of equation (3.11), and the measurements are shown by:

◇ Control

◆ 0.1 M H_3PO_4

□ 0.2 M H_3PO_4

■ 0.5 M H_3PO_4

△ 1% $CaSO_4$

▲ 2% $CaSO_4$

x 5% $CaSO_4$

The large value of the parameter κ of the soil treated with phosphoric acid indicates that the strength of larger aggregates is much lower than that of the smaller aggregates. The calcium treated soil, on the other hand, had a smaller κ value compared to the control and phosphoric acid treated soil. This indicates that the tensile strength of soil aggregates treated with calcium sulphate is little influenced by aggregate volume. These results are consistent with the mechanism by which phosphoric acid and calcium sulphate react with soil as discussed previously. For the phosphoric acid treated soil, the primary soil particles are bound into larger particles separated by flaws. In this case, larger aggregates would be more likely to contain larger flaws, and hence the soil might be expected to fracture at a lower stress. As suggested, calcium sulphate forms insoluble compounds which are distributed between soil particles. These compounds fill in the flaws, so that the flaws have a much reduced influence on tensile strength and the tensile strength of the smaller aggregates is not much different from that of the larger aggregates.

It is suggested that equation (3.7) which was firstly developed by Braunack *et al.* (1979) is a measure of soil friability. The friability of a soil can be expressed by the value of the parameter κ. A value of $\kappa = 0$ applies for a classical, ideal-plastic (non-friable material), and a k value greater than 0.4 indicates that the soil is so friable that it is mechanically unstable. The results in Table 3.10 and Figure 3.16 indicate that phosphoric acid application increased soil friability, whereas calcium sulphate application decreased soil friability. A further discussion on soil friability is presented in section 5 and in Utomo and Dexter (1981a).

Compression resistance

Changes in soil tensile strength due to chemical treatment were followed by changes in the resistance of bed of aggregates of 2.0 - 4.0 mm diameter to compression (Figure 3.17). The data found were fitted to equation (3.7). The resulting values of the parameters D_f, D_m and m (Table 3.11) are very interesting. When D_f only is considered, it might be concluded that phosphoric acid increased the compression resistance as shown by a low D_f value, and calcium sulphate, on the other hand, decreased compression resistance (high D_f value). In fact, this was not the case with the stresses actually used. As shown in Figure 3.17, with the same applied stress, the packing density of calcium sulphate treated soil is lower than that of the control and of the phosphoric acid treated soil. Thus the most important parameter in equation (3.5) is the m parameter (stress retardation). The low m value for the phosphoric acid treated soil indicates that the final equilibrium packing density given in Table 3.11 has nearly been achieved. The high m value for the calcium sulphate treated soil, on the other hand, indicates that the final packing density given in Table 3.11 is still far from being obtained. Even, this value might never be obtained, because at high stresses level (higher than stress retardation) the stress-packing density relationship would probably change. As can be seen in Figure 3.17, up to the highest stress applied, the increase in packing density with applied stress is more or less still linear. After reaching stress retardation (in this case is about 40 - 70 kPa) this relationship should no longer be linear, and hence the final packing density should not be far from the packing density at the stress retardation (here is around 0.520 - 0.550). Since in aggregated soil, at low water content, compression occurs as result of aggregate rupture (Dexter, 1975; Kezdi, 1979), then as a consequence of the decrease in tensile strength, phosphoric acid should

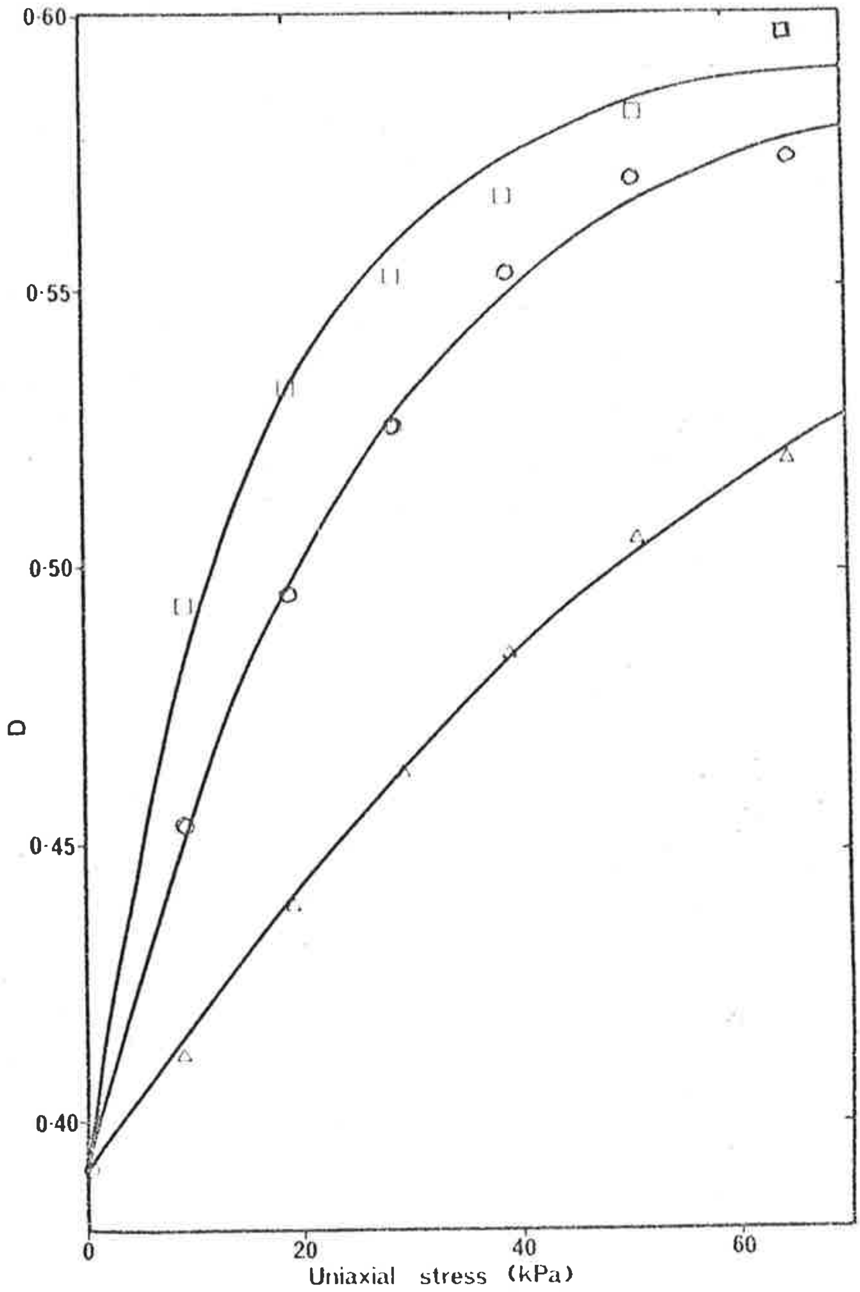


Fig. 3.17. Effect of chemical treatment on the compression resistance of beds of aggregate of Urrbrae loam, as shown by stress-packing density relationship. The continuous curves are fit of equation (3.), and the measurements are given by ○ (control); □ (H_3PO_4(0.2 M); △ $CaSO_4$ (2%).

Table 3.11. Values of D_f, D_m, and m parameters of equation (3.7) resulting from compression tests on beds of aggregates of 2.0 - 4.0 mm diameter of Urrbrae loam as influenced by chemical treatment.

Treatment	D_f	D_m	m (kPa)
control	0.596(±0.006)	0.286(±0.005)	27.12(±1.98)
0.1M H_3PO_4	0.587(±0.002)	0.195(±0.003)	17.47(±0.85)
0.2M H_3PO_4	0.590(±0.008)	0.198(±0.010)	15.75(±2.39)
1% $CaSO_4$	0.629(±0.004)	0.240(±0.004)	43.33(±1.69)
2% $CaSO_4$	0.624(±0.038)	0.236(±0.036)	78.13(±18.63)
5% $CaSO_4$	0.641(±0.01)	0.252(±0.010)	47.89(±3.87)

reduce the compressive strength. Calcium sulphate, on the other hand, since it increased aggregate tensile strength, should increase the compressive strength. An increase in the compressive strength of beds of aggregates with increasing tensile strength of the individual aggregates was found by Braunack and Dexter (1978). To make a comparison, the data in this experiment (all treatments combined) and those for natural field aggregates given in Braunack and Dexter (1978) were fitted to

$$H/H_i = N + n \exp(-n'S/\sigma_T), \qquad (3.12)$$

where H and H_i and the height and the initial height of the sample, S is the applied stress, and N, n and n' are adjustable parameters. The resulting equations were

$$H/H_i = 0.63 + 0.36 \exp(-3.84\ S/\sigma_T) \qquad (3.13a)$$

and

$$H/H_i = 0.73 + 0.25 \exp(-1.43\ S/\sigma_T) \qquad (3.13b)$$

for the combined data in this experiment and those in Braunack and Dexter (1978) respectively.

3.3 Conclusions

Some agricultural soils exhibit appreciable thixotropic behaviour around the water content at which tillage is usually performed. This behaviour can be evaluated by probe penetration, tensile strength, compression resistance as well as by shear strength measurements.

Ageing, after remoulding or disturbing these soils, results in an increase in the shear strength, tensile strength, compressive strength, and penetration resistance. These changes might have some significance in agricultural practice. The increase in the penetration resistance and tensile strength might influence seed germination and the growth of plant roots. Much work has been done to study the effect of penetration resistance on root growth, and an excellent review has been published by Barley and Greacen (1967). The effect of soil tensile strength on root elongation rate, however, has not yet been investigated. These types of investigations could have an interesting future in relation to thixotropic phenomenon. Koenigs (1961) has related thixotropic hardening to the growth of rice. He suggested that a flocculated mud is a better environment in which to grow rice then either a paste or a granulated soil.

The fact that matric water potential becomes more negative with ageing after remoulding or disturbing the soil could have some negative effects on seed germination or crop growth. Soil water previously available for seed germination or crop development may become unavailable due to this change. In addition, the rate of water movement (to plant organs) might be influenced by the increase in soil strength. It has been shown that the rate of seed germination and primary root elongation are reduced when the seed is enclosed by soil of high strength because of the restriction of water imbibition (Collis-George and Williams, 1968).

The increase in the compression resistance with ageing could be taken into account in soil management practice. It has been suggested that tillage disturbs or remoulds a soil to some extent (Dexter and Tanner, 1974; Godwin and Spoor, 1977; Utomo and Dexter, 1981b). When such a soil exhibits thixotropic behaviour, allowing the soil to rest for several days before any other activity is performed could have a significant effect in reducing compaction damage.

In the second experiment, it has been shown that adding chemicals to a soil can have effects on the strength regain behaviour resulting from ageing at constant water content. Addition of phosphoric acid or calcium sulphate increases the age hardening ratio. This result supports the conclusion drawn by some earlier workers (Rosenqvist, 1955; Seed *et al.*, 1960) that adding some chemical compounds to a soil can increase the sensitivity of the soil.

It has been found that phosphoric acid decreases aggregate tensile strength, and increases soil friability. An application of these findings is that the phosphoric acid should not be used on a soil which already has aggregates of low tensile strength. Although phosphoric acid can increase aggregate water stability as has been shown by many workers (e.g. Yeoh, 1979) the soil could suffer excessive compaction damage as a result of the reduction of tensile strength. Phosphoric acid would be more useful if it is used in a hard strong soil. In this soil, the double beneficial effects of phosphoric acid, that is an increase in aggregate water stability and soil friability could be expected. Phosphoric acid might also be useful in restoration of some soils which have been degraded by the formation of hard-pan layers.

Application of calcium sulphate increased the tensile strength of soil aggregates, and hence the resistance of beds of these aggregates to compression. It would, therefore, be more valuable if calcium sulphate is applied in a soil with aggregates with an initially low tensile strength. By doing this, the double beneficial affect of calcium sulphate, that is an increase in aggregate water stability and a decrease in the susceptibility of the soil to compaction can be attained.

SECTION 4

EFFECT OF WETTING AND DRYING CYCLES ON FORMATION AND WATER STABILITY OF SOIL AGGREGATES.

4.1 Introduction

The results of some earlier workers on the effects of wetting and drying cycles have been discussed extensively in section 2. It has been shown that wetting and drying cycles assist the formation of soil aggregates, especially in non-aggregated puddled soil (McHenry and Russell, 1943; Woodburn, 1944; Richardson, 1976). Wetting and drying cycles have been shown to decrease aggregate water stability (Willis, 1955; Tisdall *et al.*, 1978), but they also have been shown to increase aggregate water stability (Sillanpaa and Webber, 1961; Hofman, 1976).

In this work, the hypothesis was that wetting and drying cycles might initiate the formation of soil aggregates through the particle rearrangements and the formation of planes of weakness. Similarly, in aggregated soil, wetting and drying cycles could also influence aggregate water stability. The direction in which this change might occur could depend on many factors, such as the mechanism by which aggregates are formed, and the previous management of the soil.

To study these suggestions, experiments on effects of wetting and drying cycles on aggregate formation and water stability were done on some red brown earth soils from South Australia.

4.2 Materials and Methods

Soils

The soils used were from the Urrbrae, Strathalbyn and Mortlock experimental stations of the Waite Institute. These soils are red brown earths, and some properties of these soils have been described in section 3.

Aggregate formation

Samples from the A horizons of these soils were passed through a 0.25 mm sieve, and then remoulded at water contents slightly above their plastic limits. After allowing them to equilibrate overnight, these samples were remoulded again for about 2 minutes, and soil balls with diameters of about 40 - 50 mm were made by rolling these remoulded soils by hand. To minimize any effects from age hardening, the balls were pre-aged for 2 weeks at -100 kPa on a pressure plate.

These balls were then treated as follows:

a. control : the balls were kept at -1 kPa potential. The other balls were subjected to two cycles of wetting and drying between the following matric water potentials.

b. -1 kPa and -10 kPa.

c. -1 kPa and -20 kPa.

d. -1 kPa and -100 kPa.

e. -1 kPa and oven dried ($60^{o}C$).

f. -10 kPa and -100 kPa.

g. -10 kPa and oven dried ($60^{o}C$).

h. -20 kPa and oven dried ($60^{o}C$).

Wetting was done on sintered funnels, and drying was done on sintered funnels (-10 and -20 kPa), in pressure plate apparatus (-100 kPa) and in an electric oven ($60^{o}C$ oven dried). One cycle of wetting and drying consisted of wetting, then drying and rewetting. To complete 2 cycles of wetting and drying, the balls were again dried and rewetted. After completing the cycles of wetting and drying, all treatments were air dried for 10 days, and the formation of soil aggregates was assessed by the wet sieving method.

The soil balls were put onto a series of sieves (2.0, 1, 0.5 and 0.25 mm), then immersed in distilled water. For the Urrbrae and Mortlock soils, the balls were wetted completely for 15 minutes. The Strathalbyn soil needed a longer time (30 minutes). The sieves, with the balls on them, were then shaken up and down (20 mm amplitude with a frequency of 40 times per minute) for 15 minutes.

The aggregates retained on each sieve were oven dried and weighed. During wet sieving, all the aggregates passed the 2.0 mm sieve. The results were expressed as the proportion of aggregates of 0.25-2.0 mm diameter. Three measurements were made for each treatment of each soil.

Aggregate water stability

Aggregates of 2.0 - 4.0 mm diameter were collected by dry sieving from the A horizons of these soils, and then air dried. For the Urrbrae and Strathalbyn soils, the aggregates were collected from tilled and untilled plots. Tillage was done with a tyne implement to a depth of about 10 cm, and the aggregates were collected immediately after tillage from between the tractor's wheel tracks. For the Mortlock soil the experiment was done on aggregates from an untilled plot only.

These aggregates then were wetted to matric potentials of -1 kPa in sintered funnels, and then treated as follows:

a. control : kept at -1 kPa potential.
b. subjected to 1, 2, 3, 4, 6 and 8 cycles of wetting (-1 kPa) and drying (-100 kPa).

Wetting was done on sintered funnels, and drying was done in a pressure plate apparatus. After completion of the wetting and drying cycles all treatments were equilibrated to -1 kPa matric potential for two days, after which their water stability was evaluated.

Aggregate water stability was evaluated by the wet sieving method. 20 g of each treatment for each soil was put onto a series of sieves (2.0, 1.0, 0.5 and 0.25 mm), and then immersed in distilled water for 5 minutes. These sieves, with the aggregates, were shaken up and down as described previously for 30 minutes. The aggregates retained on each sieve were oven dried and weighed. The results were calculated as the proportion of aggregates > 0.5 mm diameter.

4.3 Results and Discussion

Aggregate formation

It was found that wetting and drying cycles could result in the formation of water stable aggregates (Table 4.1). It seems that planes of weakness (micro-cracks) which were formed by alternate wetting and drying were able to provide the initial faces of soil aggregates as has been suggested by White (1966). Thus, when there was a sufficient force to break the soil mass, such as a more intensive wetting (when air dry soil mass was wetted suddenly prior to wet sieving) or mechanical forces (the action of water while the sieves were shaken up and down), this soil mass could fracture along the planes of weakness to form soil aggregates. This mechanism has also been proposed by Hewitt and Dexter (1980) in studying the effect of tillage and stubble management on the structure of swelling soil. In that case, however, the force breaking up the soil was a tillage implement, and the aggregates formed were not evaluated in terms of water stability. A similar conclusion could also be drawn from the work of Ojeniyi and Dexter (1979a) who found that the structure produced by tillage in a more intensively wetted and dried soil (pasture) had a higher proportion of fine aggregates.

Table 4.1. Effect of 2 cycles of wetting and drying on the formation of water stable aggregates of 0.25 - 2.0 mm diameter.

The potential (kPa) to which the soil was wetted and dried	% aggregates 0.25 - 2.0 mm	
	Strathalbyn	Mortlock
A. Control	9.47	6.02
B. -1 and -10 kPa	10.68	9.05
C. -1 and -20 kPa	13.39	8.88
D. -1 and -100 kPa	16.62	18.07
E. -1 and oven dried (60°C)	15.60	16.33
F. -10 and -100 kPa	5.65	4.74
G. -10 and oven dried (60°C)	4.32	3.37
H. -20 and oven dried (60°C)	3.57	3.66
LSD 5%	3.77	2.69

Table 4.1 also shows that the greater is the range of potentials over which the soil was wetted and dried, the larger is the proportion of aggregates of 0.25 - 2.0 mm diameter. This is consistent with the mechanism by which wetting and drying assists the formation of soil aggregates proposed above. It was reasonable to expect that the more the soil is wetted and dried, the greater are the stresses produced by the wetting and drying. As a result, the formation of planes of weakness would be more intensive, with the consequence that the number of aggregates formed (when there was enough force to break the soil mass) would be greater. It has been shown elsewhere that the rate of breakdown of a soil mass into finer fractions increased as the rate of wetting increases (Emerson and Grundy, 1954; Panabokke and Quirk, 1957). The rates of wetting between different water potentials are shown in Figure 4.1.

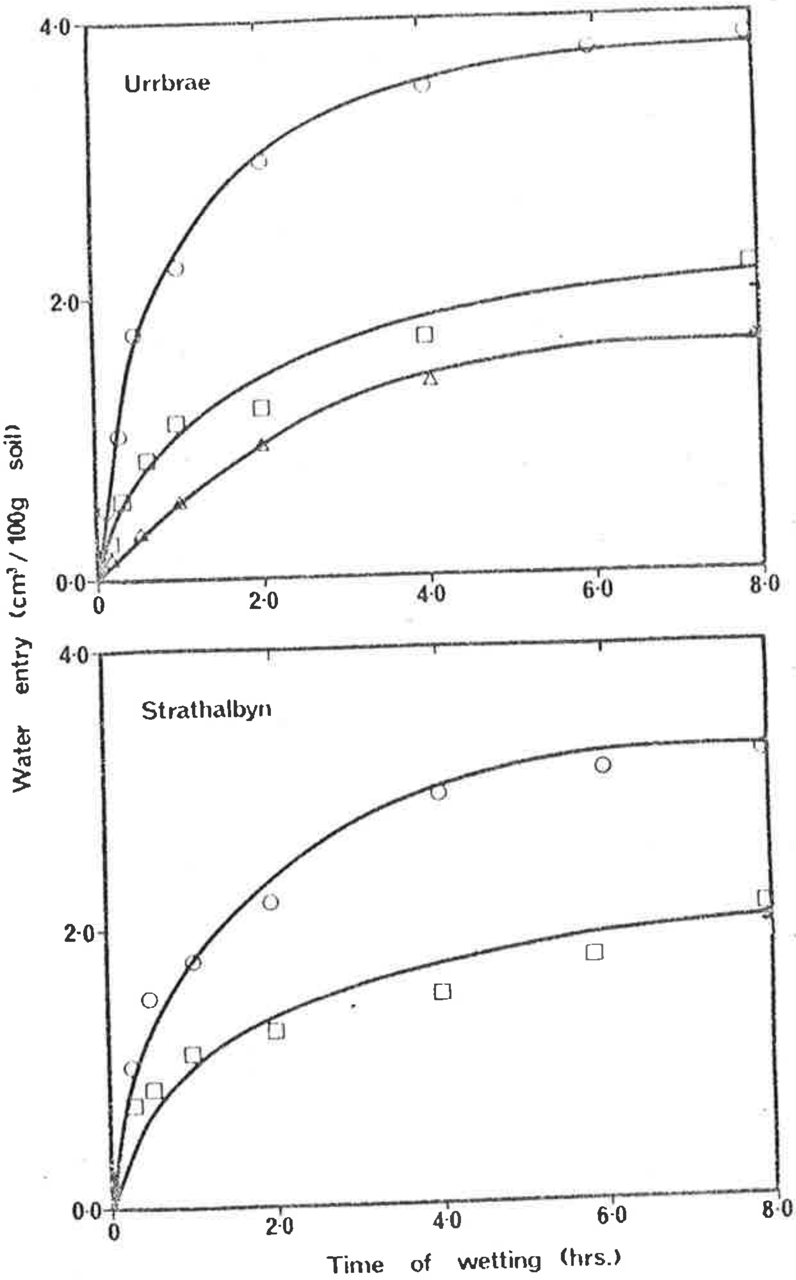


Fig. 4.1. Wetting rate as influenced by the initial matric potential and the matric potential to which the soil is wetted.

○ : -100 kPa to -1 kPa
□ : -100 kPa to -5 kPa
△ : -10 kPa to -1 kPa

In studying the formation of soil aggregates in terms of the concept of stresses and strains produced by wetting and drying, Van de Graff (1978) found that rapid rates of wetting and drying produced smaller-sized aggregates, and slow rates of wetting and drying produced larger-sized aggregates.

In addition to the mechanism suggested above, desiccation which causes orientation of water dipoles as suggested by McHenry and Russell (1943) might also contribute to the formation of soil aggregates found in this experiment.

Baver *et al.* (1972) suggested that aggregates formed by wetting and drying such as are not stable to water. To obtain water stable aggregates, there must be another process, such as the formation of cementing bonds caused by microorganism activity or bonds formed by other soil constituents.

To study the importance of soil microorganism activity in forming water stable aggregates, the following experiment was carried out. A sample of the Urrbrae soil was passed through a 0.25 mm sieve, and remoulded at a water content slightly above the plastic limit (20%) with (a) deionized water, and (b) a solution containing mercuric chloride and sodium azide. After allowing this soil to equilibrate overnight, this soil was remoulded again, and soil balls with diameter of 40 - 50 mm were made by rolling this remoulded soil by hand. These soil balls then treated as follows:

(a) control (kept at -1 kPa), and

(b) subjected to 1, 2, 4 and 6 cycles of wetting (-1 kPa) and drying (-100 kPa).

For the sterilized soil, the sintered funnels and pressure plate on which the soil was wetted and dried, were connected to reservoirs of the mercuric chloride and sodium azide solution.

The result is shown in Figure 4.2. It can be seen that the percentage of aggregates 0.25 - 2.0 mm diameter increased with increasing wetting and drying cycles both in sterilized and unsterilized soil. This tendency occurred also in the Mortlock soil (unsterilized). Again, this result supports the suggested mechanism by which wetting and drying assists aggregate formation. With increasing numbers of cycles of wetting and drying (probably to a maximum value), it can be expected that increasing numbers of planes of weakness are formed. Thus one would expect that increasing numbers of small aggregates would be formed with increasing numbers of wetting and drying cycles. This result is in good agreement with that of McHenry and Russell (1943) who found that the percentage of aggregates larger than 0.25 mm diameter increased with increasing wetting and drying up to 20 cycles. Woodburn (1944) found that the formation of aggregates of 0.5 - 2.0 mm increased with increasing wetting and drying up to two cycles, but decreased on further wetting and drying cycles. The result shown in Figure 4.2 also demonstrates the importance of soil microorganism activity in forming water stable aggregates. When soil microorganism activity was restricted, although wetting and drying cycles were still capable of forming water stable aggregates, the percentage of aggregates formed was much lower compared to that when soil microorganism activity was unrestricted.

With the formation of planes of weakness and/or particle rearrangements due to wetting and drying there should be a change in the porosity or pore size distribution of the soil. This phenomenon was studied on the Strathalbyn soil. A sample of this soil was passed through a 0.25 mm sieve, and remoulded at a water content slightly above the plastic limit (20%). After equilibration overnight, the soil was remoulded again and soil aggregates with diameters of about 15 - 20 mm were made by rolling this remoulded soil by hand. To minimize any effects resulting

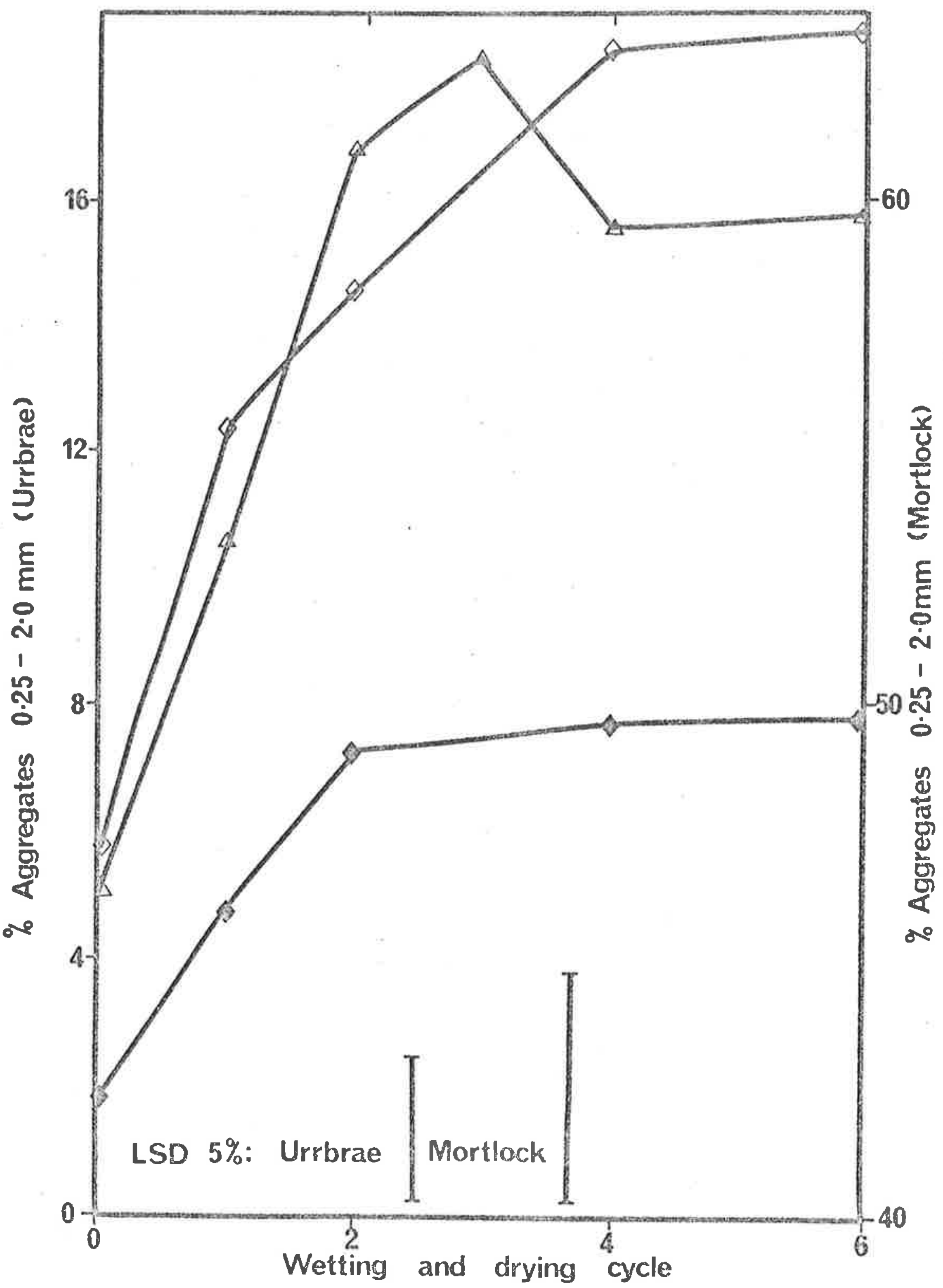


Fig. 4.2. Effect of wetting and drying cycles on aggregate formation in initially nonaggregated soils. For the Urrbrae soil, the wet-sieving was done for 15 mins. and for the Mortlock soil it was done for 10 mins.

◇ Urrbrae unsterilized ◈ Urrbrae sterilized △ Mortlock from thixotropic changes, these aggregates were aged at -20 kPa potential in sintered funnels for two weeks. These aggregates then treated as follows:

(a) control (the aggregates were kept at -20 kPa matric potential) and

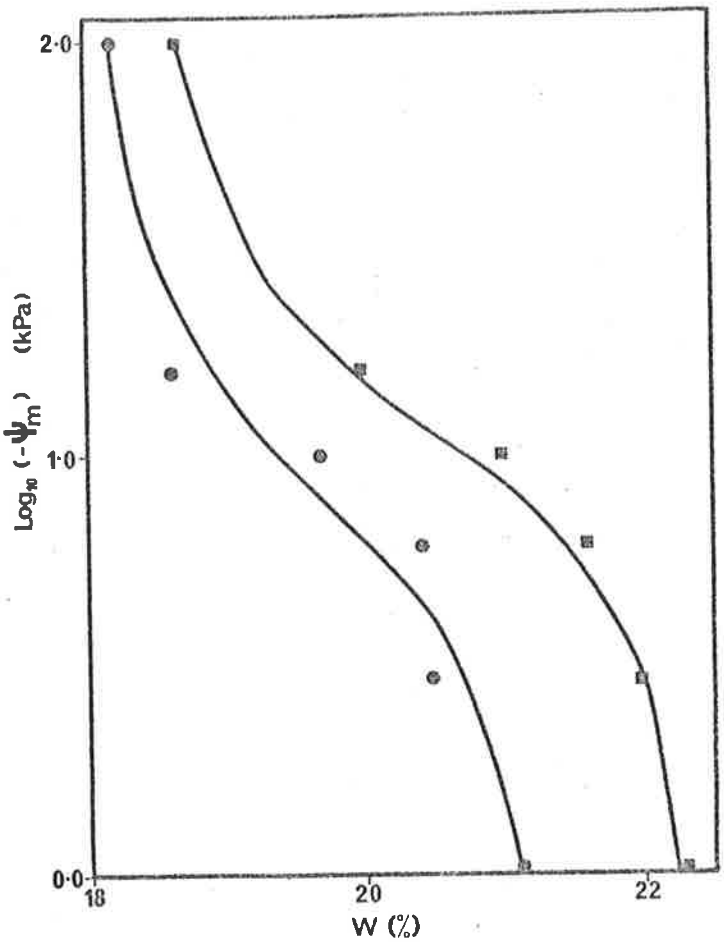
(b) subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

After the cycle of wetting and drying, all treatments were wetted to -0.5 kPa potential for two days, and then dried to -1, -3, -6, -10, -15 and -100 kPa for two days, after which the water content was determined gravimetrically. Three replicates were done for each treatment at each level of matric potential. Each replicate contained 3 - 4 soil aggregates.

The result (Figure 4.3a) supports the above suggestion. Unlike thixotropic changes which only create large pores (small pores disappeared) as discussed in section 3, wetting and drying creates small pores as well as large pores. The change in pore size distribution with wetting and drying is given in Figure 4.3b. This is reasonable because the pores created by wetting and drying are formed not only by particle rearrangement, as in thixotropic changes, but also by the formation of cracks. Coughlan and Fox (1977) used soil bulk density to evaluate the change in porosity with wetting and drying. They found that as aggregates formed (by wetting and drying cycles), the bulk density decreased.

Aggregate water stability

The effect of wetting and drying cycles on water stability of aggregates collected from untilled soils differs from that collected from tilled soil (Figure 4.4). Figure 4.4 shows that the water stability of non-cycled aggregates collected from tilled soil was much lower than that of those collected from non-tilled soil. This result demonstrates a.



b.

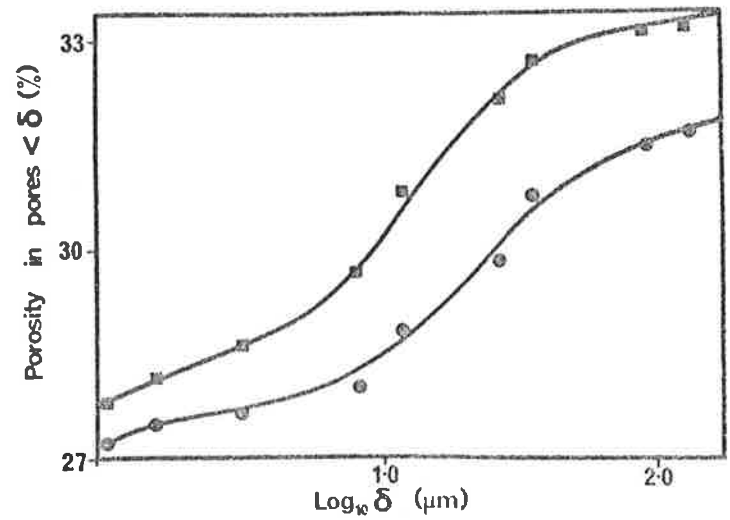


Fig. 4.3. Effect of one cycle of wetting (-1 kPa) and drying (-100 kPa) on water characteristics (a) and pore size distribution (b) of ● : control; ■ -wetted and dried.

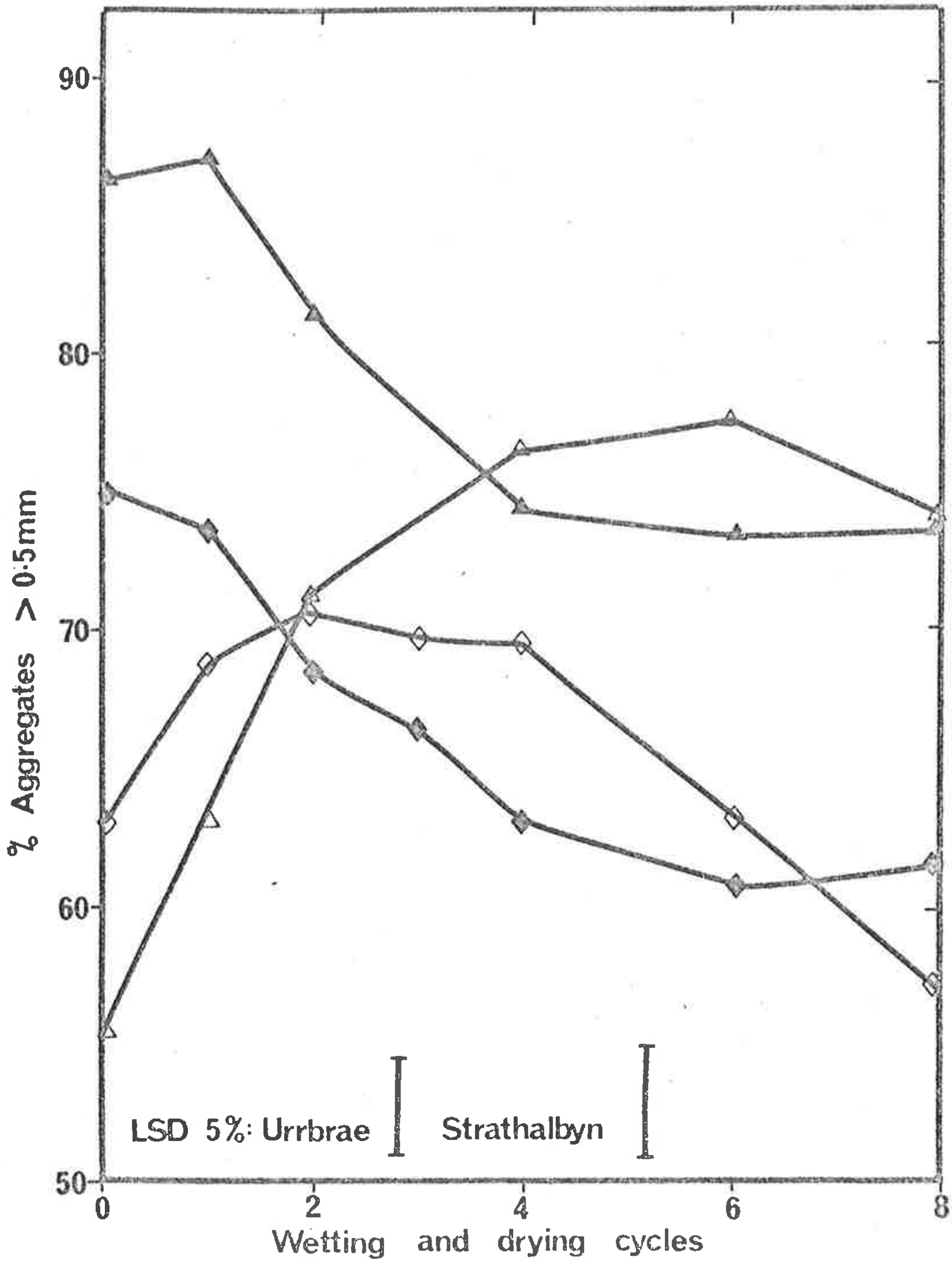


Fig. 4.4 Effect of one wetting and drying cycle on water stability of soil aggregates with initial diameter 2.0 - 4.0 mm.

◇ : Urrbrae tilled; ◆ : Urrbrae non-tilled

△ : Strathalbyn tilled ▲ : Strathalbyn non-tilled that tillage destroys much of the previous bonding within soil aggregates so that their water stability decreases. A similar result has been found by Rovira and Greacen (1957) in a laboratory experiment.

Wetting and drying of soil aggregates collected from the tilled soils first resulted in an increase in aggregate water stability (up to 4 - 6 cycles), and further increase in wetting and drying cycles decreased aggregate water stability. This shows that wetting and drying might promote the reformation of bonds which have been destroyed by tillage. It has been suggested that soil disturbance by tillage makes available some of the soil organic matter previously unavailable for microorganism activity (Rovira and Greacen, 1957). With this increase in energy resource, soil microorganism activity can increase, so that organic bonds which have been disturbed and broken by tillage can be restored. This bond reformation might be speeded up by wetting and drying cycles. An increase in microbial activity with soil wetting and drying has been shown by many workers (e.g. Birch, 1958; Agarwal, Singh and Kanehiro, 1971).

An increase in water stability of aggregates disturbed by tillage due to wetting and drying has also been found by Rovira and Greacen (1957). They, however, did not extend their observations to further cycles. Tisdall *et al.* (1978), on the other hand, found that wetting and drying aggregates disturbed by tillage steadily decreased aggregate water stability. It seems that the tillage treatment in this experiment was not able to destroy and/or rearrange soil aggregates to make unavailable organic matter available for microorganism activity. Since there was no additional energy source, the microorganisms were probably not able to replace readily the bonds which had been destroyed by wetting and drying. This suggestion is in agreement with the result found on the effect of wetting and drying cycles on water stability of aggregates collected from untilled soil. These aggregates were obtained by dry sieving the air dried sample, thus little disturbance occurred. As can be seen in Figure 4.4, after 2 - 3 cycles of wetting and drying the water stability of these aggregates decreased significantly. As in the first experiment, here it is thought that wetting and drying caused the formation of planes of weakness. When the aggregates were subjected to a greater force (when they were sieved) these aggregates broke down into finer fractions.

As discussed previously, the increase in water stability of soil aggregates disturbed by tillage with wetting and drying is thought to be due to microbial activity. To test this suggestion, the following experiment was carried out.

Aggregates of 2.0 - 4.0 mm from the tilled plot of the Urrbrae and Strathalbyn soil, and from untilled plot of Mortlock soil were wetted to -1 kPa potential in sintered funnels connected to a solution of mercuric chloride and sodium azide. Then, these aggregates were treated as follows:

(a) control (the aggregates were kept at -1 kPa) and

(b) the aggregates were subjected to 1, 2, 4 and 6 cycles of wetting (-1 kPa) and drying (-100 kPa).

Wetting and drying and aggregate water stability evaluation was done as described before.

The result (figure 4.5) shows that in the absence of microorganism activity, aggregate water stability decreased steadily with increasing wetting and drying cycles. This is consistent with the suggestion discussed previously. Since soil microorganism activity was restricted, the bonds which had been destroyed by tillage could not be reformed.

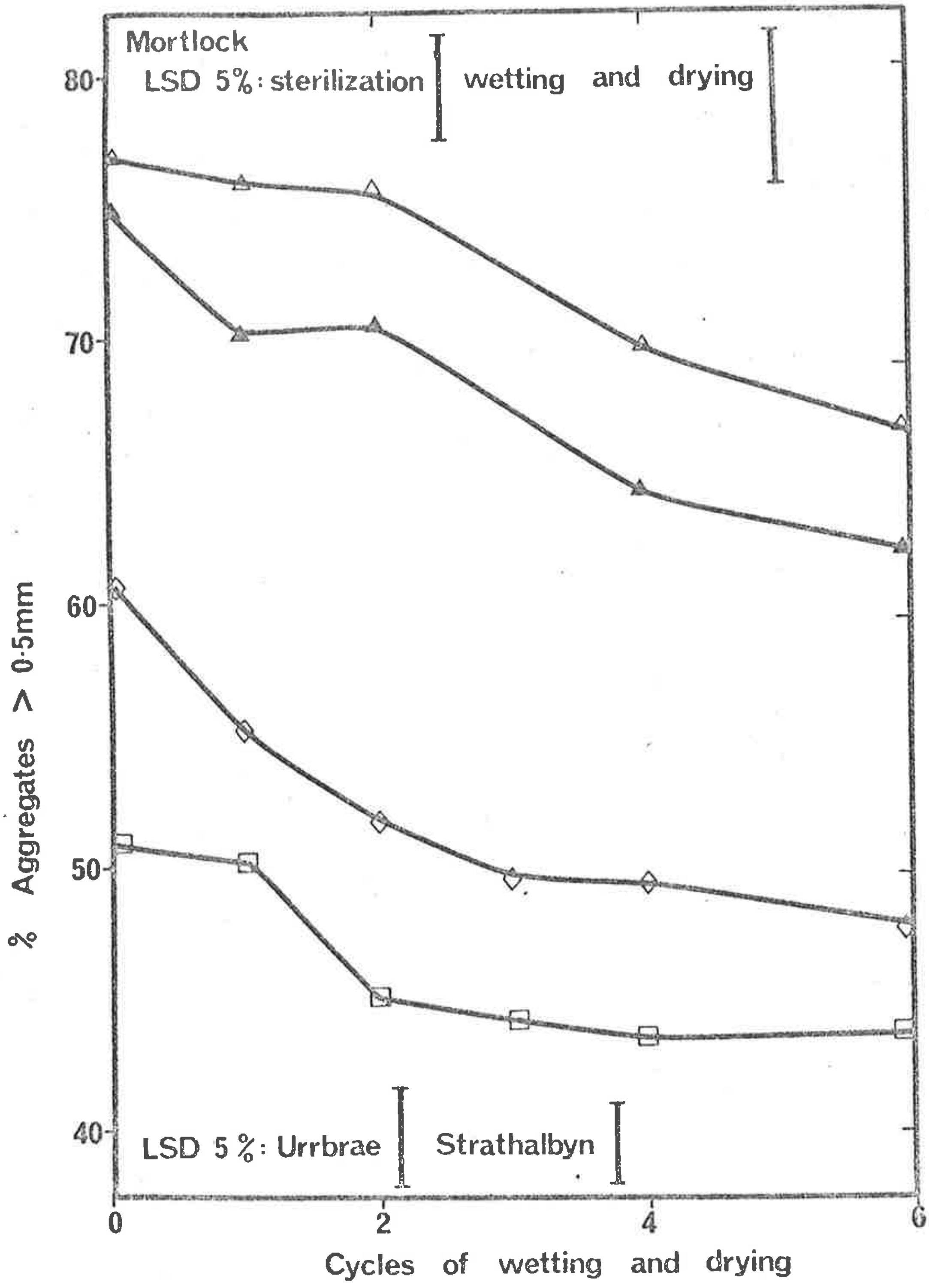


Fig. 4.5. Effect of wetting and drying cycles on water stability of soil aggregates with initial diameter of 2.0 - 4.0 mm, as influenced by sterilization.

◇ : Urrbrae sterilized (tilled)

□ : Strathalbyn sterilized (tilled)

△ : Mortlock unsterilized (non-tilled)

▲ : Mortlock sterilized (non-tilled)

With the additional formation of planes of weakness, wetting and drying even decreased aggregate water stability. Tisdall *et al.* (1978) found that the decrease in aggregate water stability in sterilized samples occurred much greater extent than in unsterilized samples. In this experiment, the water stability of sterilized aggregates (Mortlock soil) at each cycle of wetting and drying was lower than that of unsterilized soil aggregates.

4.4 Conclusions

This work shows that wetting and drying cycles influence both the formation and water stability of soil aggregates.

In a non-aggregated (puddled) soil, wetting and drying creates planes of weakness which provide initial faces of soil aggregates. The existence of these planes of weakness allows soil to break-up more readily under the action of mechanical stress into finer soil aggregates. This aggregation, especially in forming water stable aggregates, might be assisted by the rearrangement of soil particles caused by wetting and drying. With this finding, it is suggested that, for many purposes, soil structure can be improved by subjecting the soil to alternate wetting and drying.

The effect of wetting and drying cycles on water stability of soil aggregates was influenced by the mechanism by which the aggregates were formed. It has been found that the water stability of aggregates disturbed by tillage first increased to a maximum value, and then decreased with increasing numbers of wetting and drying cycles. For natural (undisturbed) aggregates, wetting and drying cycles steadily decreased the water stability.

The increase in water stability of aggregates disturbed by tillage is suggested to be a consequence of increased microbial activity. When the energy source for microbial activity is a limiting factor as with undisturbed soil, aggregate water stability decreases with wetting and drying cycles. This idea is supported by the results obtained with sterilized samples. It is therefore suggested that the incorporation of plant residues in tillage could provide an additional energy source for soil microorganism activity. It could then be expected that the water stability of aggregates disturbed by tillage would increase so that the risk of aggregate breakdown and hence run-off with consequent soil erosion, could be minimized.

SECTION 5

EFFECT OF WETTING AND DRYING ON SOIL STRENGTH

5.1 Effect of wetting and drying cycles on soil strength

5.1.1 Introduction

It has been shown (section 4) that wetting and drying a soil influences both the formation and water stability of soil aggregates. With the assumption that one of the processes causing these phenomena originates from particle movement or/and reorientation (McHenry and Russell, 1943), it is likely that the attractive and repulsive forces which determine the interparticle cohesion change with wetting and drying. It is, therefore, reasonable to suggest that wetting and drying cycles influence soil strength.

In the past, most experiments have been limited to the study of the effect of either wetting or drying individually on soil strength (Winterkorn, 1942; Gill, 1959; Gerard *et al.*. 1961; Gerard, 1965; Camp and Gill, 1969). It has been suggested that the increase in soil strength with drying is one of the important factors responsible for the formation of pan layers in some soils of the United States (Gerard *et al.*, 1961; Taylor, Mathers and Lotspeich, 1964). It has been suggested that this increase is caused by the increase in attraction forces due to closer packing of soil particles (Gerard, Cowley and Kunze, 1966). In addition, cementation which can develop during drying (Lambe, 1960), has also been thought to be one of the factors which increases soil strength (Ingles, 1962). An increase in the shear cohesion (C) and the coefficient of soil internal friction (tan Ø) with drying has been found by Camp and Gill (1969).

In another study, Gerard (1965) found that the method of drying influenced the end effect of drying on soil strength. He suggested that the cohesive action of water molecules during slow drying was similar to the action of Na^+, i.e. to increase close packing, and therefore, soil strength. Fast drying resulted in a lower strength due to the disruptive action of escaping water molecules on the arrangement of soil particles. Baver *et al.* (1972) realized that on rapid drying the dehydration of the soil mass can not be uniform. This gives rise to unequal strains throughout the soil mass, and results in the formation of planes of weakness, such as cracks. Strength decrease due to cracks can be predicted by the Griffith (1921) theory, and the contribution of cracks to the reduction in strength of materials has been extensively studied for a range of materials such as rocks (Walsh, 1965), ceramics (Williamson, 1960), and stabilized soils (Ingles and Lafeber, 1966). The mechanism of crack formation and propagation, mainly due to an applied stress has been discussed by Ingles and Lafeber (1967), and a statistical analysis of cracks in soil aggregates has been developed by Braunack *et al.* (1979).

Wetting generally results in weakening and may lead to a collapse of some structures. The movement of water molecules into a soil mass tend to weaken the cohesive forces (Winterkorn, 1942; Rogowski and Kirkham, 1976) and can result in a considerable reduction of the strength. The stresses and strains developed by unequal swelling of the soil, and stresses developed by entrapped air may also be involved in weakening soil bonds with a consequent decrease of soil strength.

Winterkorn and Fehrman (1944) found that after subjecting their soil samples to 12 cycles of wetting and drying, the bearing capacity decreased almost to zero. A decrease in soil strength due to wetting and drying cycles has also been observed by Gibbs *et al.* (1960). The shear cohesion of a soil which had an initial value of about 28 kPa decreased to about 15 kPa after one cycle of wetting and drying, and to about 6.5 kPa after 2 cycles of wetting and drying. Gerard, *et al.* (1962) used penetration resistance as a measure of soil strength, and found that penetration resistance increased with increasing number of wetting and drying cycles.

Carnes (1934) and Lemos and Lutz (1957) related wetting and drying to the formation of soil crusts. Carnes (1934) found that rapid drying produced crusts which broke easily, whilst slow drying produced stronger crusts. Lemos and Lutz (1957) extended this study by investigating the effect of wetting and drying cycles on crust strength. They found that wetting and drying cycles decreased the modulus of rupture of the crust. A decrease in the modulus of rupture with wetting and drying cycles was also found by Sharma and Agrawal (1979).

The object of the work described here was to study the effect of wetting and drying cycles on the strength of soil. If wetting and drying cycles influence soil strength, then it might be worthwhile to consider this change in soil management practice. Possible applications of these changes will be discussed.

5.1.2 Materials and Methods

Soils

The soils used were the Urrbrae, Strathalbyn, Mortlock, and Waco soils. Some properties of these soils have been described in section 3.

Remoulded aggregates

Samples from the A horizons of these soils were passed through a 1.0 mm sieve, and remoulded at water contents slightly above the plastic limits with distilled water. These samples were allowed to equilibrate overnight, and then were again remoulded for about 2 minutes. Aggregates of about 10 mm diameter were made by rolling these remoulded soils by hand. These aggregates then treated as follows:

(a) Control 1 (the aggregates were stored at -100 kPa matric water potential).

(b) Control 2 (the aggregates were stored at -1 kPa matric water potential).

(b) The aggregates were subjected to wetting and drying cycle(s) between different water potentials.

One cycle of wetting and drying consisted of drying, then wetting, and redrying. Wetting and drying was done in sintered funnels (for potentials less negative than -100 kPa) and in pressure plate apparatus (for potentials more negative than -100 kPa). Each wetting or drying was done for 2 days.

Prior to strength measurement, all treatments were dried to the potential of -100 kPa in a pressure plate apparatus for 2 days. The tensile strengths of 16-20 aggregates were measured by crushing the aggregates individually between parallel plates (Rogowski, 1964; Dexter, 1975) as described in section 3, and the tensile strength, σ_T, was calculated from

$$\sigma_T = 0.576 \, F/\pi \, d^2 \qquad (5.1)$$

where F is the force required to crush the aggregate until fracture occurs, and d is the aggregate diameter.

Soil cores (Brazilian test)

Samples from the A horixon of the Urrbrae and Mortlock soils were passed through a 1.0 mm sieve, and remoulded at water contents slightly above the plastic limits. After allowing these samples to equilibrate overnight, they were again remoulded and pressed into plastic cores of 24 mm diameter and 15 mm height. These cores then treated as follows:

(a) Control (the cores were stored at -100 kPa matric water potential).

(b) The cores were subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

Wetting and drying was done as described before. Prior to the measurement of the strength, all treatments were dried to the potential of -100 kPa in a pressure plate apparatus for 2 days. The tensile strength was measured by the Brazilian method. The core was placed on its side on a horizontal plate, and a crushing force, F, was applied through another horizontal plate above the core until the core ruptured. Tensile strength, σ_T, was calculated from the equation (Kirkham *et al.*, 1959)

$$\sigma_T = \frac{2F}{\pi d l} \tag{5.2}$$

where d is the diameter of the core, and l is the core length.

15 cores were prepared for each treatment of each soil. It was decided to compare tensile strengths measured by the Rogowski-Dexter method (called the aggregate tensile strength) with that measured by the Brazilian test, (called the core tensile strength). To do this, both tests were done on (non-cycled soil) Urrbrae untreated, Urrbrae phosphoric acid treated, and Strathalbyn, Mortlock and Waco soils.

Penetration resistance

Samples from the A horizon of the Urrbrae and Mortlock soils were passed through a 1.0 mm sieve and remoulded at water contents slightly above the plastic limits. After allowing these soils to equilibrate overnight, they were again remoulded for about 2 minutes, and then pressed into plastic cores of 24 mm diameter and 15 mm height.

These cores then treated as follows:

(a) Control (the cores were stored at -100 kPa matric water potential).

(b) The cores were subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

Wetting and drying was done as described before. Prior to the strength measurement, all treatments were dried to the potential of -100 kPa in a pressure plate apparatus for 2 days. The penetration resistance was measured by a motor driven laboratory penetrometer as described in section 3. The penetration resistance, Q_p, was calculated by

$$Q_p = 4 F/\pi d^2 \tag{5.3}$$

where F is the force required to push the probe to a depth of 5 mm, and d (= 1.00 mm) is the probe diameter. 3 measurements were done on each of 10 cores for each treatment of each soil.

Field clods and aggregates

Clods of about 100-150 mm diameter were collected from a tilled plot of the Urrbrae soil at various numbers of days after tillage. The tillage system is described in section 6. These clods were then wetted to near saturation by capillary action, and then treated as follows:

(a) Control (the clods were stored at -100 kPa matric water potential).

(b) The clods were subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

The strength of clods which was determined after all treatments were dried to -100 kPa potential for 2 days, was determined by the drop shatter test (Marshall and Quirk, 1950; Gill and McCreery, 1960; Ingles, 1963). Each clod was dropped from a height of 200 cm, and then the size distribution of the resulting clods/aggregates was measured by dry sieving. 8 clod strength were determined for each treatment for each time of sampling.

In addition to those measurements, the tensile strengths of smaller aggregates were measured. Aggregates with diameters of 4.0-9.5 mm were collected from tilled and non-tilled plots of the Urrbrae and Strathalbyn soils. These aggregates were wetted by capillary action, and then treated as follows:

(a) Control (the aggregates were stored at -100 kPa matric water potential).

(b) The aggregates were subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

The strengths of 20 aggregates of each treatment for each soil were determined as described before.

5.1.3 Results and Discussion

Tensile strength of soil aggregates and soil cores

Before comparison of the tensile strength values obtained by the Rogowski-Dexter method (soil aggregates) with those obtained by the Brazilian test (soil cores), it is interesting to compare the tensile strengths of different sized cores measured by the Brazilian test. Two core sizes (8 cores of each size) of 24 mm (diameter) X 10 mm (height) and 14 mm X 14 mm were prepared from the Urrbrae, Urrbrae treated with 0.5 M H_3PO_4, Strathalbyn, Mortlock and Waco soils. The results showed that there was a tendency for a greater tensile strength for the 24 X 10 mm cores than for 14 X 14 mm cores. The mean tensile strengths for these 5 soils were 29.1 kPa (for 24 X 10 mm cores) and 26.7 kPa (14 X 14 mm).

It was found that tensile strength measured by the Rogowski-Dexter method (soil aggregates) was sigificantly lower than that found by the Brazilian test (soil cores) (Table 5.1). This is not entirely surprising. This difference may have originated partly from differences in sample preparation. The samples for remoulded aggregates were prepared by rolling the remoulded soil by hand. Thus little pressure was involved. The cores, on the other hand, were prepared by pressing the soil into plastic cylinders, which involved a relatively greater

Table 5.1. The tensile strength of remoulded soils as influenced by the method of measurement.

Soils	Tensile strength (kPa)	
	aggregates (16 mm diameter)	cores
Urrbrae untreated	23.9	31.1
Urrbrae H_3PO_4 treated	19.0	26.6
Strathalbyn	17.4	21.8
Mortlock	20.6	26.9
Waco	21.6	32.4
Mean tensile strength	20.5	27.8
LSD 5% between method	1.04	

pressure. As a comparison, the packing density for the aggregates of Urrbrae H_3PO_4 treated and Strathalbyn soils were 0.575 and 0.562, whereas the corresponding packing density for cores was 0.744. Increasing packing density often results in soil particles being closer together and this may result in greater attractive forces. Another possible reason for this difference is the uncertainty regarding the "constant" 0.576 in equation 5.1. As discussed in section 2, Rogowski and Kirkham (1976) have subsequently suggested an "improved" value of 0.821. The tensile strengths measured by the two methods used here would be equal if this value were 0.781. However, it is difficult to make an accurate comparison because tensile strength is itself a function of sample size.

Effect of wetting and drying on the strength of remoulded soils

It was found that wetting and drying can decrease the tensile strength of remoulded soil aggregates (Table 5.2). The results given in Table 5.2 show that wetting and drying between -1 and -100 kPa; -1 and -200 kPa; -5 and -100 kPa; and -5 and -200 kPa; significantly decreased aggregate tensile strength. Wetting and drying between -10 and -100 kPa did not significantly influence tensile strength. The decrease in the tensile strength with wetting and drying between -1 and -100 kPa was also found in the soil cores (Table 5.3). One cycle of wetting (-1 kPa) and drying (-100 kPa) however, did not significantly influence soil penetration resistance (Table 5.4).

When a remoulded soil is subjected to wetting and drying cycles, there are several processes which might be involved in influencing the strength. When the soil is wet enough, the first process which can be expected to occur is thixotropic change. As discussed in section 3, this change results in an increase in the strength. The second possible

Table 5.2. Effect of different potentials in wetting and drying cycle(s) on the tensile strength of remoulded soil aggregates.

Treatment	Tensile strength (kPa)			
	Urrbrae	Waco	Strathalbyn	Mortlock
Control 1 (-100 kPa)	49.3	31.1	28.6	27.5
Control 2 (-1 kPa)	46.7	-	-	-
-100 and -1 kPa*	35.8	26.6	21.7	23.6
-100 and -5 kPa	40.3	27.1	24.3	26.3
-100 and -10 kPa	48.2	28.5	25.3	26.1
-200 and -1 kPa	33.5	27.0	-	-
-200 and -10 kPa	48.9	25.9	-	-
-500 and -1 kPa	34.5	-	-	-
Aggregate diameter (mm)	8	10	10	12
Number of W&D cycles	2	2	1	1
LSD 5%	3.55	2.70	1.97	2.41

* refers to the potential to which the aggregates were dried and wetted.

Table 5.3. Effect of one wetting and drying cycle on the tensile strength of remoulded soil cores.

Treatment	Tensile strength (kPa)		
	Urrbrae	Mortlock	Means
Control (-100 kPa)	29.1	32.8	30.9
-1 and -100 kPa	24.9	28.8	26.8
LDS 5% (between treatment)			3.76

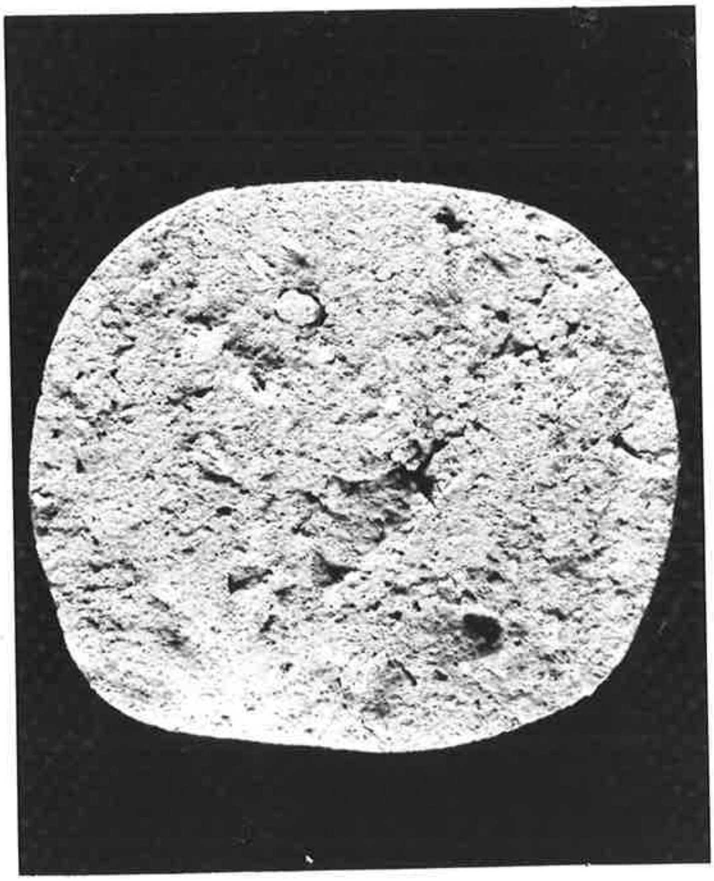
Table 5.4. Effect of one cycle of wetting and drying on the resistance of the soils to probe penetration.

Treatment	Penetration resistance (kPa)	
	Urrbrae	Mortlock
Control (-100 kPa)	3203.8	3258.1
-1 and -100 kPa	3370.4	3216.6
	NS	NS

process is the movement or/and rearrangement of individual soil particles due to wetting and drying. How this process influences soil strength might depend on the method of wetting and drying. As suggested by Gerard (1965) fast drying decreased soil strength, whereas slow drying increased the strength of the soil. The third possible process is the formation and propagation of internal cracks. The occurrence of this process is a consequence of unequal swelling and shrinkage resulting from uneven wetting and drying. The formation of cracks in remoulded aggregates caused by wetting and drying is shown in plate 5.1. In agreement with Griffith's (1921) theory, the existence of these cracks results in a decrease in the tensile strength.

The stresses and strains developed by wetting and drying between water matric potential of -1 and -100 kPa; -5 and -100 kPa; -1 and -200 kPa; -1 and -500 kPa; are high enough to initiate and propagate planes of weakness. Although there is a strength increase due to the thixotropic process (see Table 3.5, section 3.1), it seems that the decrease in the strength due to crack formation is much greater, so

Plate 5.1. Micro-cracks in remoulded soil aggregates formed by wetting and drying (magnification of 8 times).



that the net result is a decrease in the tensile strength. The penetration resistance, on the other hand, is not influenced by this change. This is presumably because the compressive soil failure mode for a penetrometer shown in Figure 2.3 can not take advantage of these cracks.

It seems that the stresses and strains produced by wetting and drying between matric potentials of -10 and -100 kPa were not high enough to create planes of weakness. Or if there was crack formation, it was not intensive enough, and the decrease in the strength caused by this process was compensated by the increase in the strength due to the thixotropic process. Thus there was no net change in tensile strength.

From Table 5.2, it can be seen that the less negative the potential to which the soil is wetted, the greater is the decrease in the tensile strength. As shown in section 4 (Figure 4.2) the rate of wetting is greater when soil is in contact with a source of water at a less negative matric potential. This indicates that with increasing wetting rate, the stresses and strains set up by unequal swelling increase, and hence cracks form more readily. In addition, the breakdown of soil bonds occurs more intensive as the rate of wetting increases (Emerson and Grundy, 1954). This suggestion is supported by the result given in Table 5.5 which show that although the aggregates were wetted to the same matric water potential (B, C and D) and (E and F), the tensile strength can be different. The greater the rate of wetting, the lower the tensile strength. The rate of wetting in treatment B was greater than that in treatments C and D, so that the tensile strength of aggregates subjected to B treatment is lower than that of those subjected to C and D treatments. A similar tendency occures in treatment E compared with treatment F.

Table 5.5. Effect of wetting method of a wetting and drying cycle on the tensile strength of remoulded aggregates of Urrbrae soil.

Treatment	Tensile strength (kPa)
A. Control (-100 kPa)	40.2
B. -100 and -1 kPa	24.7
C. -100 and -10, -1 kPa	35.3
D. -100 and -10, -5, -1 kPa	36.3
E. -100 and -5 kPa	36.2
F. -100 and -10, -5 kPa	40.8
aggregate diameter (mm)	8.6
LSD 5%	2.47

As discussed previously, the decrease in tensile strength of aggregates subjected to one cycle of wetting and drying between potentials of -10 and -100 kPa might be partially compensated by an increase in strength caused by the thixotropic process. To test this suggestion, remoulded aggregates were aged at -100 kPa matric water potential in a pressure plate apparatus for 2 weeks before being subjected to wetting and drying. These aggregates then treated as follows:

(a) Control (the aggregates were stored at -100 kPa matric water potential).

(b) The aggregates were subjected to one cycle of wetting and drying between potentials of -1 and -100 kPa; -5 and -100 kPa; and -10 and -100 kPa.

Prior to the measurement of the strength, all treatments were dried to the potential of -100 kPa in a pressure plate apparatus for 2 days. The results (Table 5.6) show that when the thixotropic process has virtually ceased (after 2 weeks ageing) a cycle of wetting and drying of -10 and 100 kPa significantly decreased aggregate tensile strength.

The tensile strength of both freshly remoulded and aged aggregates of the Urrbrae soil decreased with increasing numbers of cycles of wetting (-1 kPa) and drying (-100 kPa). For freshly remoulded aggregates the minimum tensile strength occurs at 2 cycles, and then slightly increased with further cycles of wetting and drying. For the aged aggregates, a decrease in the tensile strength occurs up to 4 cycles of wetting and drying, beyond which further wetting and drying cycles do not significantly influence the tensile strength (Figure 5.1). For the aged aggregates, the decrease in tensile strength with wetting and drying cycles, $\sigma_{T(n)}$, was fitted to the exponential equation

$$\sigma_{T(n)} = A + a\,[1 - \exp(-a'n)] \qquad (5.4)$$

Table 5.6. Effect of one cycle of wetting and drying on tensile strength of aged aggregates.

Treatment	Tensile strength		
	Urrbrae	Strathalbyn	Waco
Control (-100 kPa)	53.7	34.8	34.4
-100 and -1 kPa	40.2	29.3	29.4
-100 and -5 kPa	47.1	29.3	29.8
-100 and -10 kPa	48.9	31.1	26.8
Aggregate diameter (mm)	8.6	10	10
LSD 5%	3.39	2.22	3.31

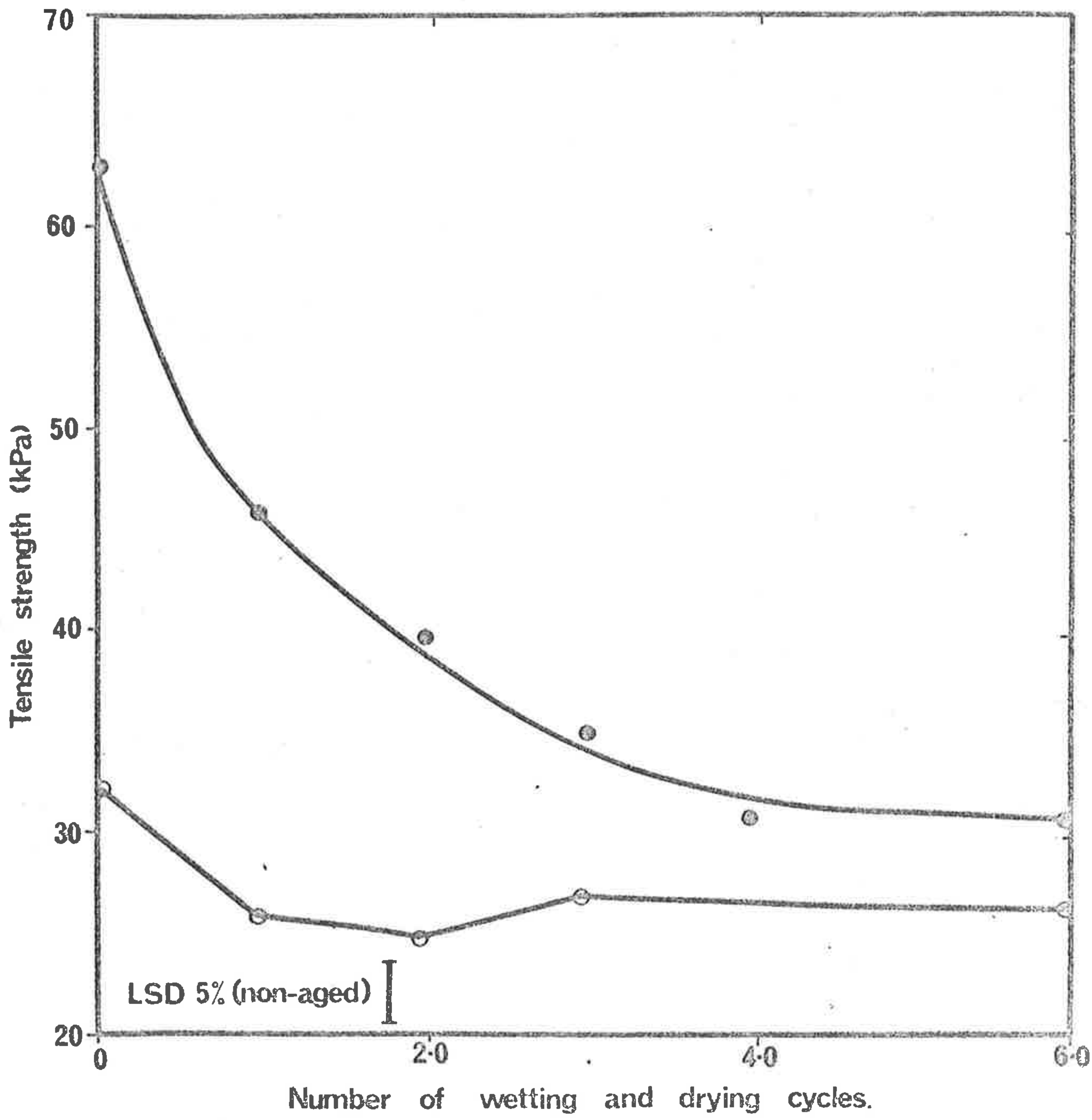


Fig. 5.1. Effect of wetting and drying cycles on the tensile strength of remoulded aggregates of Urrbrae loam.
○ : non aged aggregates,
● : aged aggregates (for this treatment the continuous curve is equation (5.5)).

where A, a, and a' are adjustable parameters and n is the number of wetting and drying cycles. The resulting equation is

$$\sigma_{T(n)} = \underset{(\pm 1.134)}{62.19} - \underset{(\pm 2.091)}{32.81} \left[1 - \exp(\underset{(\pm 0.10)}{-0.61}n)\right] \quad (5.5)$$

A similar tendency was also found when aggregates made from the Strathalbyn soil were wetted and dried between -1 kPa and -100 kPa (Figure 5.2). The aggregates of the control treatment of this soil were stored at -20 kPa matric water potential in sintered funnels. The results for non-aged Strathalbyn aggregates (5.4) gave

$$\sigma_{T(n)} = \underset{(\pm 0.37)}{26.62} - \underset{(\pm 0.43)}{8.09} \left[1 - \exp(\underset{(\pm 0.16)}{-1.14}n)\right] \quad (5.6)$$

Field clods and aggregates

Wetting and drying clods collected from tilled soil can also influence clod strength (Table 5.7). When the clods were collected at 0 days and 7 days after tillage, wetting and drying decreased clod strength. This was shown by the fact that the proportion of aggregates smaller than 4.0 mm diameter resulting from the drop shatter test in the wetted and dried clods was greater than that in the control. For the clods collected 20 days after tillage, on the other hand, one cycle of wetting and drying did not significantly influence clod strength. It is probable that these clods had then reached an equilibrium value of strength where further wetting and drying could not cause further soil break up.

For soil aggregates (4.0 - 9.5 mm), one cycle of wetting and drying influenced the strength of aggregates from non-tilled Strathalbyn soil, but did not significantly influence the strength of aggregates from non-tilled Urrbrae soil (Table 5.8). Further, Table 5.8 shows that a

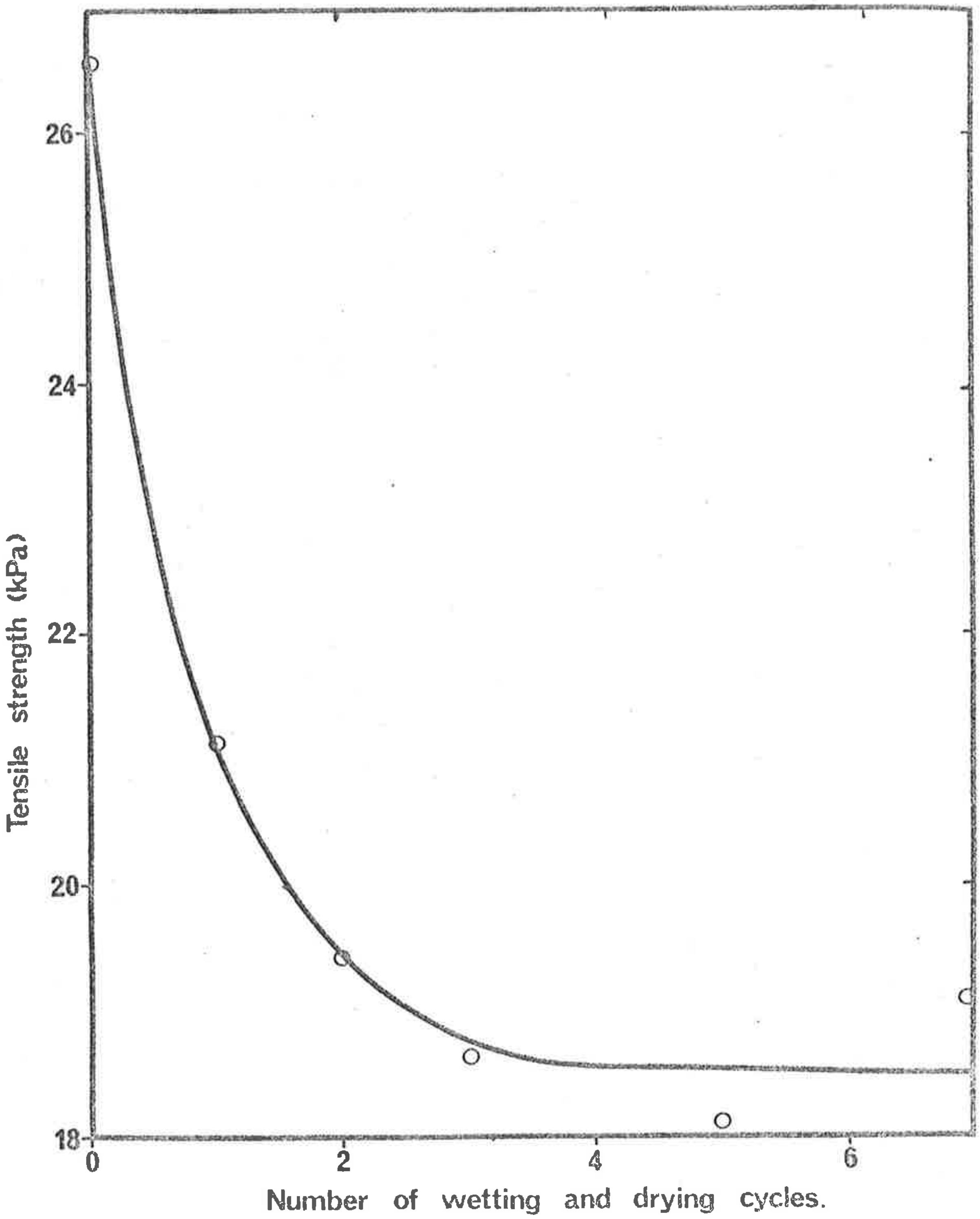


Fig. 5.2. Effect of wetting and drying cycles on the tensile strength of remoulded (non aged) Strathalbyn aggregates. The continuous curve is a plot of equation (5.5).

Table 5.7. Effect of one cycle of wetting and drying on clod strength, as shown by the proportion of aggregates < 4.0 mm produced by the drop shatter test, of the Urrbrae tilled soil.

Treatment	% aggregates < 4.0 mm days after tillage		
	0	7	20
Control (-100 kPa)	20.2	28.6	37.4
-100 and -1 kPa	27.3	34.5	36.0
LSD 5%		5.79	

cycle of wetting and drying between water matric potentials of -10 and -100 kPa significantly decreased the tensile strength of the larger aggregates (6.7-9.5 mm), but did not significantly influence the tensile strength of the smaller aggregates (4.0-6.7 mm). This phenomenon will be considered further when discussing soil friability (section 5.2).

Table 5.8. Effect of one cycle of wetting and drying on the tensile strength of aggregates from non-tilled soil.

Treatment	Tensile strength (kPa)			
	Urrbrae		Strathalbyn	
	aggregate diameter (mm)			
	4.0-6.7	6.7-9.5	4.0-6.7	6.7-9.5
Control (-100 kPa)	22.1	16.0	25.0	21.5
-100 and -1 kPa	22.8	16.9	20.6	16.4
-100 and -10 kPa	22.6	15.7	24.8	16.9
LSD 5%	: between aggregate : size : 2.37		: 3.48	

For the field aggregated collected from tilled soil, it was found that a cycle of wetting and drying significantly decreased the tensile strength of the larger aggregates (6.7-9.5 mm). It can be seen in Table 5.9, that for the smaller aggregates (4.0-6.7 mm), the decrease in the tensile strength is not significant at the 5% probability level.

Table 5.9. Effect of one cycle of wetting and drying on the tensile strength of aggregates from tilled Urrbrae soil.

Treatment	Tensile strength (kPa) aggregate diameter (mm)	
	4.0-6.7	6.7-9.5
Control (-100 kPa)	28.1	26.2
-100 and -1 kPa	26.7	19.7
-100 and -10 kPa	28.9	24.2
LSD 5%	2.48	

Effect of ageing on the strength of aggregates which have been weakened by wetting and drying

The following experiment was designed to study the effects of ageing on the tensile strength of soil aggregates previously weakened by wetting and drying cycles. Remoulded aggregates of the Urrbrae and Waco soils were made as described before. These aggregates were aged at -100 kPa matric water potential in a pressure plate apparatus for two weeks, then treated as follows:

(a) Control (the aggregates were stored at -100 kPa).

(b) The aggregates were subjected to one cycle of wetting (-1 kPa) and drying (-100 kPa).

After the cycle of wetting and drying, all treatments were subjected to the potential of -100 kPa in a pressure plate apparatus for 2 days. The tensile strengths of 16 aggregates of each treatment for each soil were measured as described before, and the remainder were kept at -100 kPa for later testing.

The results (Table 5.10) shows that ageing (until 8 days) did not result in any significant change in tensile strength of aggregates which had been weakened by wetting and drying.

Table 5.10. Effect of ageing on the tensile strength of soil aggregates which have been weakened by one cycle of wetting (-1 kPa) and drying (-100 kPa).

Ageing (days)	Tensile strength (kPa) Urrbrae control	Urrbrae W & D	Waco control	Waco W & D
0	54.6	47.1	26.8	22.3
4	56.3	46.8	27.6	22.3
8	54.3	48.8	27.2	22.9
Mean tensile strength	55.1	47.6	27.2	22.5
LDS 5% between means	5.72		2.38	
Aggregate diameter (mm)	8.6		12	

Temperature cycling

In nature, wetting and drying are usually accompanied by temperature changes. In order to try to isolate the factor primarily involved in decreasing aggregate tensile strength, an experiment was done to test any effects of temperature changes on the mechanical properties of soil aggregates.

The experiment was done on both natural and artificial aggregates from the Urrbrae fine sandy loam. Natural aggregates of 10-13 mm diameter were collected from the A horizon of the Urrbrae soil. Artificial aggregates were made by rolling the remoulded Urrbrae soil as described before. To eliminate any effects resulting from thixotropic hardening, these artificial aggregates were aged at -100 kPa matric water potential in a pressure plate apparatus for two weeks. Then both the natural and the artificial aggregates were air dried, after which they were treated as follows:

(a) Control (1) : the aggregates were stored at a constant temperature of 10°C.

(b) Control (2) : the aggregates were stored at a constant temperature of 50°C.

(c) The aggregates were subjected to temperature cycling between 10°C and 50°C for 1, 2, 3 and 4 cycles.

Prior to strength measurement, all treatments were subjected to a matric water potential of -153 MPa over saturated $CaCl_2$ solution in a vacuum desiccator for two weeks. The tensile strengths of 16 (for artificial) and 20 (for natural) aggregates were measured by crushing the aggregates individually between flat parallel plates until fracture occurred, as described before.

The results (Table 5.11) show that temperature cycling did not significantly influence the tensile strength of either natural or artificial aggregates. This result supported the hypothesis that the decrease in aggregate tensile strength is chiefly caused by the formation of cracks due to unequal swelling and shrinkage resulting from wetting and drying.

Table 5.11. Effect of temperature cycles on the tensile strength of natural and artificial aggregates of Urrbrae soil.

Treatment (temperature cycling)	Tensile strength (kPa) Natural	Artificial
Control 1 (10^{o}C)	46.5	417.9
Control 2 (50^{o}C)	47.5	417.5
1 cycle	48.3	406.0
2 cycles	48.4	406.5
3 cycles	48.9	420.9
4 cycles	48.7	400.6
	NS	NS

5.2 Soil Friability

5.2.1 Introduction

The application of conventional soil mechanics to tillage (e.g. Payne, 1956) predicts that the size of the primary fragments sheared from the undisturbed (bulk) soil is independent of the shear cohesion and only slightly influenced by the angle of internal friction. Whilst this theory has been proved to be useful for predicting the draught forces of simple implements, is of no use in predicting soil fragmentation produced by tillage. Observation shows that different soils, or even the same soil at different water contents, fragment quite differentially. Clearly, a factor other than the conventional soil mechanical quantities quantities must be implicated.

The term "soil friability" has been defined as the tendency of a mass of unconfined soil in bulk to crumble and breakdown under applied stress into smaller fragments, aggregates and individual soil particles (Bodman, 1949). Christensen (1930) employed stress-strain relationships to attempt to measure soil friability. The modulus of rupture test (Richard, 1953) has also been used in an attempt to measure soil friability by Jamison (1954). Both of these approaches, however, only measure how easy the soil is worked, or in other words, soil strength. Neither takes account 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 comprise the large clods, have a relatively greater strength than the large clods or the bulk soil mass. Otherwise, with applied stress the soil mass could break down into individual soil particle or dust. With this consideration, the definition of soil friability given by Bodman (1949) can be modified and sharpened. In this thesis, soil friability is defined as the tendency of a mass of unconfined soil to breakdown and crumble under applied stress into a particular size range of smaller aggregates. Thus not necessarily into individual soil particles or dust.

Rogowski and Kirkham (1976) and Braunack *et al.* (1979) have found that the tensile strength of soil aggregates is a function of aggregate size. The larger are the aggregates, the smaller is the tensile strength. Braunack *et al.* (1979) showed this relationship by the equation

$$\log_e \sigma_T = K - k \log_e V \qquad (5.7)$$

where

$$K = \log_e (\sigma_{To} V_o^k \Gamma (1+k)) \qquad (5.8)$$

Here, σ_{To} and V_o are the strength and volume respectively of the basic soil elements which comprise the bulk soil aggregates, Γ is the tabulated Gamma function, k is an adjustable parameter, and the parameter k is a measure of the dispersion of the strengths of the microcracks within the aggregates. The intercept K is, in effect, an extrapolated estimate of the tensile strength of unit (1 m^3) samples of the bulk soil.

A comparison of the objectives of tillage with the definition of soil friability given in this thesis, leads to the conclusion that equation (5.7) can be used to measure soil friability. The value of k is an indicator of how easily large clods will breakdown into a range of smaller soil aggregates. Large k values indicate that the larger clods have a much smaller strength than the smaller aggregates. Thus large k values are associated with situations where the large clods have a low mechanical stability and may readily be fragmented. Fragmentation does not proceed indefinitely, however, because of the relatively greater strength and hence mechanical stability of the smaller aggregates. 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 unit volume of soil element which comprise these large clods. In this case, when a mass of this soil is subjected to applied stress, such as by tillage, it will break up into clods and aggregates of arbitrary size.

As a result of these considerations, in this thesis the parameter k of equation (5.7) is identified as a measure of soil friability, and discussed as a quantity separate from soil strength. Thus a soil of any strength can have any value of friability, k.

5.2.2 Materials and Methods

Effect of soil water content

As discussed in section 2.1.4, soil water content at tillage influences the size distribution of the resulting clods (Lyles and Woodruff, 1962; Bhushan and Ghildyal, 1972; Ojeniyi and Dexter, 1979a). Since there is an optimum 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 (5.7), also occurred at a similar water content.

Aggregates with diameter 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 the Urrbrae and Strathalbyn soils. These aggregates were air dried, and then wetted slowly by capillary action close to saturation in sintered funnels. These aggregates then dried to matric water potentials of -10 kPa (in sintered funnels), -50, -100 and -500 kPa (in pressure plates) for two days.

The tensile strengths of 20 aggregates of each diameter class at each water content for each soil were measured by crushing the aggregates individually between parallel plates (Rogowski, 1964; Dexter, 1975) as done in section 5.1.

Wetting and drying

It has been shown (section 5.1) that cycles of wetting and drying are able to decrease aggregate tensile strength. In the field, any increase in amplitude of wetting and drying can result in greater soil fragmentation on tillage. The later is the "tilth mellowing" effect and is discussed in section 6. Consideration of these phenomena, led to the suggestion that wetting and drying cycles are capable not only of decreasing aggregate tensile strength, but also of increasing the friability of the soil. To test this idea, the following experiments were done.

Samples from the A horizons of Urrbrae and Mortlock soils were passed through a 1 mm sieve, and remoulded at water contents slightly above their plastic limits with distilled water. These remoulded soils were allowed to equilibrate overnight, and were then again remoulded. Aggregates with diameters of about 5, 8, 10, 13 and 17 mm were made by rolling these soils by hand. To eliminate any effects of thixotropic (age) hardening, these aggregates were aged at a matric water potential of -100 kPa in a pressure plate apparatus for two weeks. The aggregates were then treated as follows:

(a) Control : the aggregates were stored at -100 kPa matric water potential.

(b) The aggregates were subjected to different numbers of cycles of wetting and drying between different water potentials.

After wetting and drying, all treatments were subjected to a matric water potential of -100 kPa in a pressure plate apparatus for two days. The tensile strengths of 16 aggregates of each size for each treatment of each soil were determined as described before.

Freezing and thawing

In nature, the formation of flaws or cracks within the soil mass is not created by wetting and drying cycles alone. As discussed in section 2.1.3, freezing and thawing a soil may also result in the formation of cracks. The following experiment was designed to investigate effects of freezing and thawing cycles on soil friability as measured by the k value of equation (5.8).

Remoulded Urrbrae soil was treated as follows:

(a) Control : the aggregates were stored in plastic containers and placed in a constant temperature room.

(b) The aggregates were subjected to 1 and 3 cycles of freezing and thawing.

Freezing was done by placing the aggregates in a $-15^{\circ}C$ room for one day, and thawing was done at $20^{\circ}C$ for one day. After freezing and thawing, all treatments were dried to a matric water potential of -100 kPa in a pressure plate apparatus for two days. The tensile strengths of 16 aggregates of each size for each treatment were measured as described before.

5.2.3 Results and Discussion

The effect of soil water content

The effects of aggregate volume on the tensile strength, σ_T, of the Urrbrae and Strathalbyn aggregates are shown in Figures 5.3 and 5.4. Variations of the derived parameters K and k, together with the tensile strengths of 10 mm diameter aggregates, σ_{T10}, as a reference for the Urrbrae and Strathalbyn soils are given in Table 5.12.

At low water contents, aggregates of both the Urrbrae and Strathalbyn soils have a small k value and a large tensile strength. This indicates that at these water contents the soils are difficult to crush. At high water contents, the soils have relatively small strength. However, they are not suitable for tillage because the soil will turn up 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 water contents corresponding to a matric water

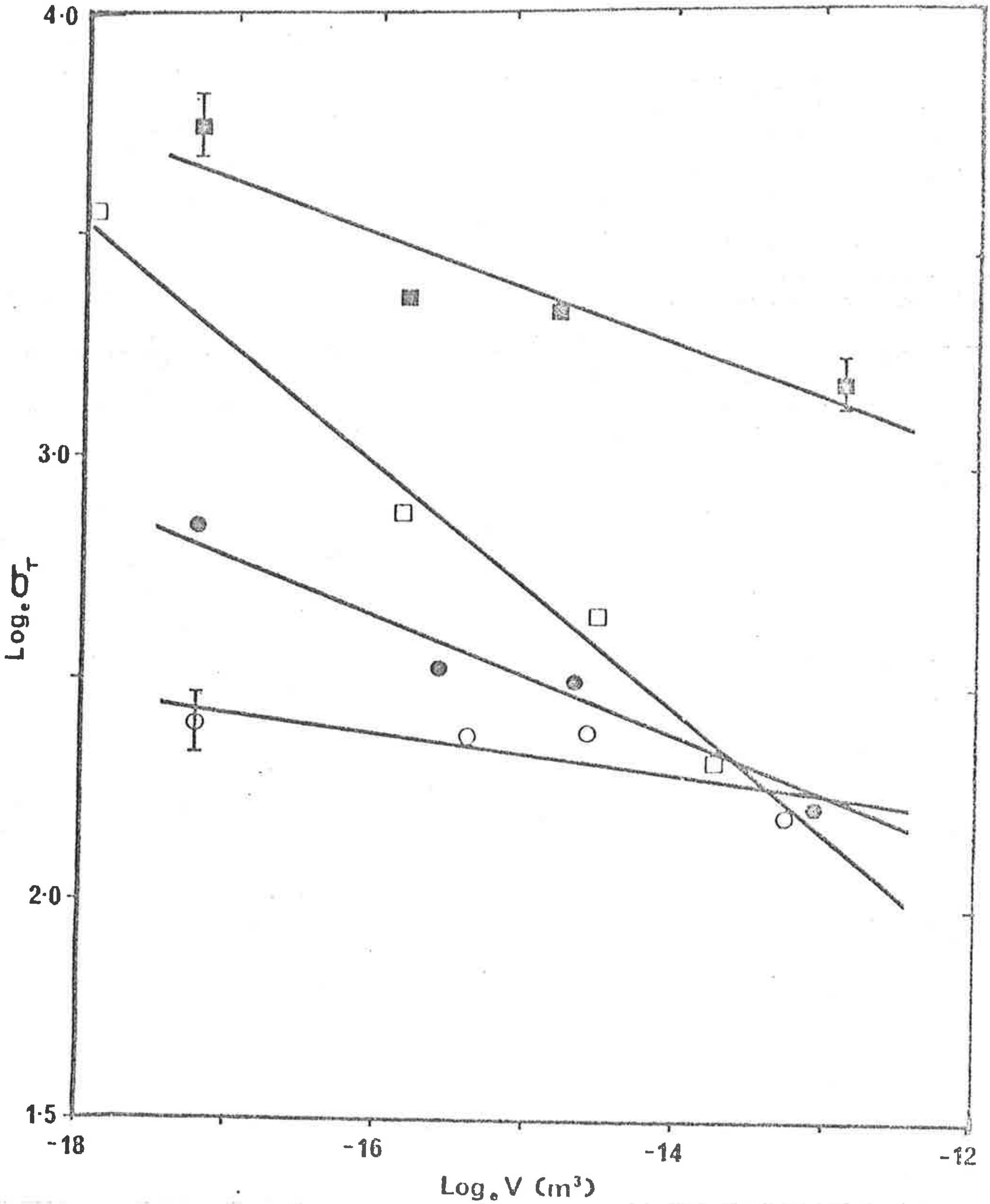


Fig. 5.3. Effect of matric water potential on the log aggregate tensile strength-volume relationship of Urrbrae loam. The continuous curves are fits of equation (5.7), and the measurements are given by ○ (-10 kPa); ● (-50 kPa); □ (-100 kPa); and ■ (-500 kPa).

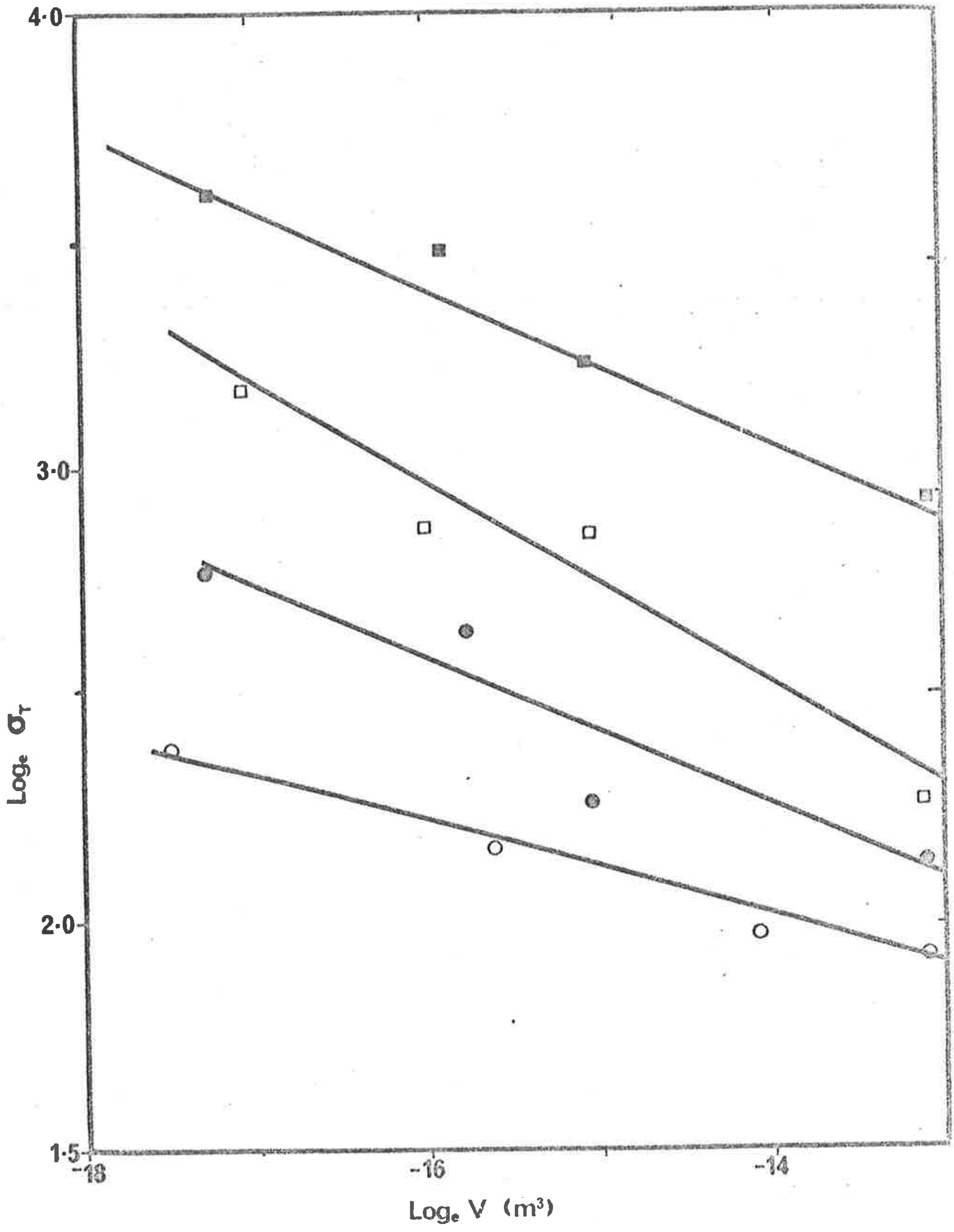


Fig. 5.4. Effect of matric water potential on the log$_e$ volume-log tensile strength relationship of Strathalbyn soil aggregates. The continuous curves are fit of equation (5.7), and the measurements are given by ○ (-10 kPa); ● (-50 kPa); □ (-100 kPa) and ■ (-500 kPa).

Table 5.12. Effect of water content on the values of parameters of K and k of equation (5.7) and on the strengths of 10 mm diameter aggregates, σ_{T10}.

Matric water potential (kPa)	Urrbrae				Strathalbyn			
	water content (%)	K (kPa)	k	σ_{T10} (kPa)	water content (%)	K (kPa)	k	σ_{T10} (kPa)
- 10	30.2	1.64	0.05	10.1	34.6	0.54	0.10	7.7
- 50	22.4	0.56	0.13	11.5	25.6	0.02	0.16	10.0
-100	18.1	-1.48	0.28	12.7	16.3	-0.55	0.22	13.5
-500	12.3	1.60	0.12	27.1	11.8	0.65	0.17	23.0
-153000*	2	3.06	0.07	59.1	-	-	-	-

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

potential of -100 kPa. These are 18.1% for the Urrbrae and 16.3% for the Strathalbyn soils. Under these conditions, the soils were considered to be friable.

Some earlier workers found that large clods were produced when tillage was done at very low or very high water contents (e.g. Lyles and Woodruff, 1962). For the Urrbrae fine sandy loam, Ojeniyi and Dexter (1979a) have found that the water content giving the maximum soil crumbling on tillage is around 0.9-1.0 of the plastic limit. This is in good agreement the observed peak in friability found in this experiment.

The k values in Table 5.12 can be fitted to quadratic equations as done in tillage experiments of Ojeniyi and Dexter (1979a). They normalized the soil water contents by dividing them by the plastic limit (PL). The intention of this was to make the results as far as possible independent of soil type. The same procedure was adopted here, and the resulting equations are

$$k = -0.32 + 1.07 \left(\frac{W}{PL}\right) - 0.54 \left(\frac{W}{PL}\right)^2, \quad r = 0.64 \qquad (5.9)$$

for the Urrbrae soil, and

$$k = 0.08 + 0.24 \left(\frac{W}{PL}\right) - 0.12 \left(\frac{W}{PL}\right)^2, \quad r = 0.86 \qquad (5.10)$$

for the Strathalbyn soil.

For both soils, differentiation shows that the maximum value of k occurs at a gravimetric water content of W = 1.0 PL. Although these equations are derived from only a few data points and have only a relatively low statistical significance, they do illustrate well this maximum value.

In their tillage experiments, Ojeniyi and Dexter (1979a) found that the proportion of aggregates, P, smaller than or equal to 4 mm in intercepted length (measured on impregnated sections) at the mid-depth of tillage varied as

$$P = -0.51 + 1.89 \left(\frac{W}{PL}\right) - 0.91 \left(\frac{W}{PL}\right)^2 \qquad (5.11)$$

A comparison of values of k from equation (5.9) with the values of P from equation (5.11) shows that the ratio P/k remains remarkably constant at 2.3 ± 0.1 over the range of water contents $0.6 < W/Pl < 1.12$. Over this range, both P and k values vary by 67% and the tensile strength of 10 mm diameter aggregates, σ_{T10}, varies by a factor of about 3.

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 is then weakened through another mechanism as a result of the increased soil water content. The reason for the observed decrease in k at small water contents is not yet understood.

Effect of wetting and drying

It was expected that the flaw severity in non-cycled remoulded aggregates would not vary much with aggregate volume. The value of k in equation (5.7) for these aggregates, then, should be close to zero. In fact, however, this is not quite the case. As shown in Figure 5.5 and Tables 5.13 and 5.14, the strength of non-cycled remoulded aggregates was still slightly influenced by aggregate size. This is shown by the fact that the k values of these aggregates were k = 0.07 for the Urrbrae soil, and k = 0.11 for the Mortlock soil. This is presumably because some flaws were formed during the slight drying and ageing processes to which these samples were subjected.

As the soil aggregates were wetted and dried, the flaw severity increased, consequently wetting and drying not only decreased the tensile strength of the aggregates, but also increased the k value. The increase in k with wetting and drying indicates that the decrease in strength in larger aggregates occurred much more rapidly than in smaller aggregates. As discussed in section 5.1, the decrease in the tensile strength of soil aggregates with wetting and drying is probably caused by the formation of cracks due to uneven swelling and shrinkage. Since wetting and drying

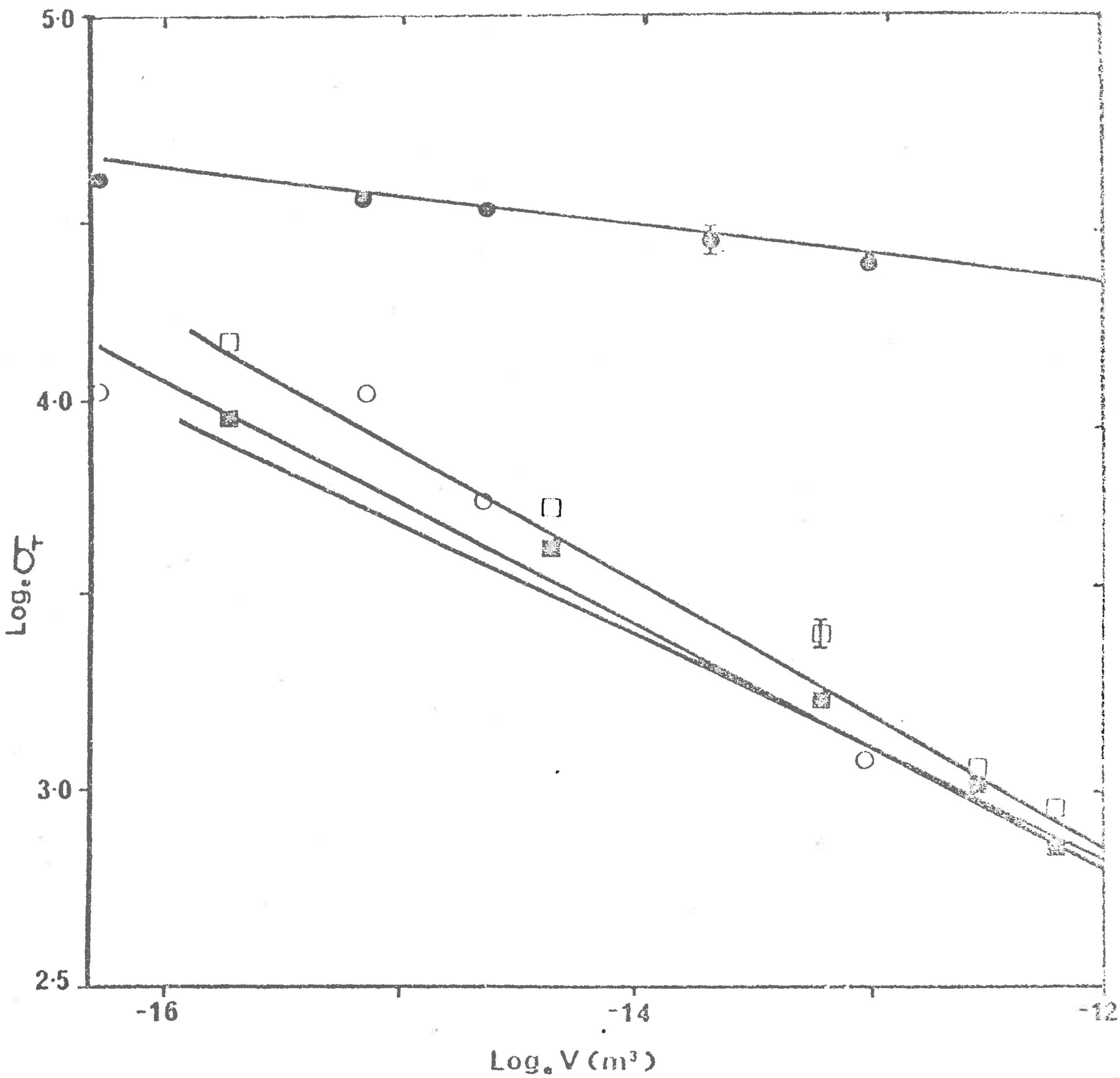


Fig. 5.5. Effect of wetting and drying cycles on the log tensile strength-volume relationship. The continuous curves are fits of equation (5.7), and the measurements are given by ● (control); ○, □ (1 cycle) and ▪ (3 cycles). Urrbrae soil.

Table 5.13. Effect of wetting (-1 kPa) and drying (-100 kPa) on the values of parameters of K and k of equation (5.7), and on the tensile strength $\sigma_{T\ d}$, of remoulded Urrbrae aggregates of diameter d (mm).

W&D cycles	K(kPa)	k	σ_{T5}(kPa)	σ_{T10}(kPa)	σ_{T20}(kPa)
Control	3.48	0.07	103.3	89.3	77.2
1 cycle	-1.15	0.33	74.4	37.4	18.8
3 cycles	-0.67	0.29	62.0	33.9	18.6
∿(field aggregates)	-1.48	0.28	23.4	13.1	7.3

Table 5.14. Effect of wetting and drying cycles on the values of parameters of K and k of equation (5.7), and on the tensile strength, $\sigma_{T\ d}$, of remoulded Mortlock aggregates of diameter (mm).

W&D cycles	K(kPa)	k	σ_{T5}(kPa)	σ_{T10}(kPa)	σ_{T20}(kPa)
Control	2.40	0.11	67.9	54.1	43.0
1 (-10 and -100kPa)	1.07	0.19	67.5	45.5	30.6
3 (-10 and -100kPa)	-0.49	0.30	87.5	46.9	25.5
1 (-1 and -100 kPa)	-0.70	0.31	83.7	43.9	41.5
3 (-1 and -100 kPa)	-0.90	0.32	80.8	41.5	21.3

is from one side (outer) only, it is likely that the wetting and drying in larger aggregates will be less homogeneous than in smaller aggregates. Consequently, the resulting stress (and hence internal flaws) due to this uneven wetting and drying will be greater in the larger aggregates.

From the data in Table 5.13, it is not possible to fit a very meaningful equation to the variation of k with wetting and drying cycles. Utomo and Dexter (1981a) fitted the tensile strength results to the equation

$$\sigma_{T\,d} = C + c \exp(-c'n) \qquad (5.12)$$

which predicts the decrease in the tensile strength of aggregates of diameter d, $\sigma_{T\,d}$, with the number of wetting and drying cycles, n. With the assumption that the C value was equal to the values of σ_T after ∞ cycles (field aggregates), they found c' values of 0.23, 0.38, and 0.52 for aggregates of 5, 10 and 20 mm diameter respectively. Although these are rather crude values, they support the previous suggestion that the decrease in the tensile strength (with wetting and drying) occurred much more rapidly in larger aggregates.

In stead of the number of wetting and drying cycles, it is probably useful to express the variation of the k value of equation (5.7) with the cumulative water content change ($\Sigma\,\Delta\,W$) which occurred during wetting and drying. This has been done for the Mortlock soil (Table 5.14). The values of $\Sigma\,\Delta\,W$ were calculated from the results given in section 3 (Figure 3) for the aged sample. The resulting equation was quadratic

$$k = 0.11 + 0.02\,(\Sigma\,\Delta\,W) - 0.0003\,(\Sigma\,\Delta\,W)^2, \quad r=0.97 \qquad (5.13)$$

and is applicable up to $\Sigma\,\Delta\,W = 40\%$.

Effect of freezing and thawing.

The effect of freezing and thawing cycles on the parameters K and k of equation (5.7), together with the strengths of 10 mm aggregates are given in Table 5.15. As in the wetting and drying process, freezing

Table 5.15. Effect of freezing and thawing cycles on the values of parameters K and k of equation (5.7), and on the tensile strength, σ_{T10}, of 10 mm diameter aggregates of remoulded Urrbrae soil.

Freezing and thawing cycles	K (kPa)	k	$\sigma_T 10$ (kPa)
Control	2.33	0.04	18.1
1 cycle	1.35	0.10	65.3
3 cycles	1.46	0.08	14.0

and thawing also decreases aggregate tensile strength and increases soil friability as shown by the increase in the value of k parameter of equation (5.7).

The weakening due to freezing and thawing cycles was also though to be caused by the formation of microcracks in the aggregates. 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% increase in the volume of water in soil when it is frozen disrupt soil bonds which result in the formation of cracks. In certain soils under certain conditions, ice lenses can be formed. Unlike the cracks produced by wetting and drying which were not so apparent, these cracks, especially the outer cracks on the aggregates, were visible to the naked eye.

5.3 Conclusions

It has been shown (section 5.1) that wetting and drying can decrease the tensile strength of remoulded aggregates, and of clods produced by tillage. The evidence suggests that the weakening process involved is the formation of planes of weakness resulting from unequal swelling and shrinkage. This finding suggests that it might be useful to control natural wetting and drying cycles in field soil management practice.

In tillage practice, one implement pass is usually not enough to produce a suitable seed bed. The use of natural wetting and drying to reduce clod strength could be achieved by allowing the soil, after the first implement pass, to dry during the day and to wet during the night for several days. The formation of planes of weakness as a result of this wetting and drying might enable the soil to be tilled more easily, and hence reduce the input energy and cost of tillage. In addition, with decreasing clod strength, it might be possible to reduce the number of implement passes, so that compaction damage by the tillage machinery can be minimized. This possibility is investigated in section 6.

In section 5.2 a measure of soil friability has been developed from a theory for the brittle fracture of soil aggregates. It seems that this can account for observed differences in the crumbling behaviour of soils.

Soil friability varies with soil water content. The Urrbrae and the Strathalbyn soils were most friable when their water contents were equal to their plastic limits. This indicates that when these and probably most other soils are tilled at this water content the large clods will break down most readily into a seed bed of relatively stable aggregates. The optimum water content predicted by this method is in good agreement with the results of tillage experiments obtained by some earlier workers.

Wetting and drying cycles, and also freezing and thawing cycles not only decrease aggregate tensile strength, but also increase soil friability as shown by the increase in the value of parameter k of equation (5.7). This is a consequence of the more intensive crack formation (due to uneven wetting and drying or freezing and thawing) in large aggregates.

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 the practical experience obtained, the following rather arbitrary classification is proposed :

$k < 0.05$	:	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. An upper bound of $k = 0.66$ applies for the case when the crushing force, F, is the same for all sizes of aggregates.

The choice of $k > 0.40$ as being mechanically unstable is consistent with the observation that larger 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 which have been 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 arable Waco soil (thought to be formed by compacting effect of machinery) fall on completely different strength-volume curves than the smaller aggregates formed by natural processes (see Figure 2 in Braunack *et al.*, 1979). Thus the strength-volume relationship must change 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 100-250 μm, which is probably the size of the basic structural elements of the larger aggregates for many soils. The discontinuities in the log(strength) - log(volume) curves, or their differentials, may be indicative of changes in the internal micro structure and particle bonding mechanism at that particular size.

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

SECTION 6

EFFECT OF NATURAL WETTING AND DRYING ON THE PROPERTIES OF TILLED SOILS

6.1 Soil water behaviour

6.1.1 Introduction

There is no doubt that tillage modifies the behaviour of soil water due to the alteration in soil structure. Usually the effect of tillage on soil water is discussed from point of view of soil water conservation (Aasheim, 1949; Allmaras, 1967). It is believed that tillage can conserve soil water. A greater net soil water content in tilled soil compared to that in non-tilled soil has been shown by Allmaras (1967). This is caused partly by greater infiltration into tilled soil (Burwell, Allmaras and Sloneker, 1966; Johnson, Mannering and Moldenhauer, 1979), and partly by reduced rates of evaporation from tilled soils (Willis, 1960; Hadas and Hillel, 1972; Hadas, 1975).

Hadas (1975) and Braunack (1979) have discussed the evaporation data of Allmaras (1967). They concluded that due to interactions of site, infiltration and non-isothermal conditions these data are difficult to interprete and are inconclusive. These data, however, are still very valuable, because there are very few data available for real field conditions. The results given by other workers (Willis, 1960; Hadas and Hillel, 1972; Hillel and Hadas, 1972; and Hadas, 1975) were obtained under artificial conditions.

It is a common assumption that in the long term, the rate of evaporation from a tilled soil is less than that of from non-tilled soil. This assumption has been supported by the results of Willis (1960) and others (e.g. Hadas and Hillel, 1972; Hadas, 1975). Evaporation rate from a real tilled soil, however, cannot be predicted with any accuracy.

The evaporation rate from the tilled layer, providing soil unsaturated hydraulic conductivity is high enough to meet evaporative demand, is often greater than that from the same layer (depth) of non-tilled soil. This is caused by the increase in the net radiation with increasing surface roughness (Allmaras, 1967). The decrease in soil heat flux after tillage (van Duin, 1954) has also been suggested as one of the factors responsible for increasing evaporation from relatively wet tilled layers. In addition, the convective movement of atmosphereic air resulting from air turbulence effects (Ojeniyi, 1978) may also contribute significantly to evaporation from this layer. Tillage, therefore, results in a drier tilled layer, but tends to conserve water in the soil beneath the tilled layer.

In discussing some results of Russian workers, Lemon (1956) came to the conclusion that evaporation of soil water after wetting could be characterized by three stages. The first stage is that rapid loss of water where capillary flow to the soil surface is sufficient to meet the evaporative demand of the above ground environment. This stage of evaporation only occurs whilst the soil profile is able to supply water to the evaporating surface at a rate satisfy the evaporative potential. As the soil profile dries out, the unsaturated hydraulic conductivity falls, and water can no longer be supplied at the potential evaporative rate. As a consequence, evaporative loss decreases rapidly, and this is known as the second stage. In this stage the rate of evaporation is controlled by the soil and the soil water. In the third stage, evaporation occurs at extremely slow rates and is governed by adsorptive forces of molecular distance at the soil liquid solid interface and by vapour diffusion in the air-filled pore space.

The external evaporative demand, E, is usually calculated from Penman's (1948) equation

$$E = (H\,\Delta + E_a\,\gamma)/\,(\Delta + \gamma) \qquad (6.1)$$

where H is the net radiation available at the surface, γ is the wet and dry hygrometer constant, $\Delta = {}^{d}e_a/d_{T_a}$ (here e_a is the saturated vapour pressure of water in the air at temperature T_a), and E_a = $(e_a - e_d)f(u)$ (here e_d is the saturated vapour pressure at the dew point, and f(u) is a function of wind speed, u.

Hanks and Woodruff (1958) have demonstrated the importance of wind speed in influencing evaporation rate. Their experiment showed that the evaporation rate from a wet soil underneath a dry mulch increased two to six times when the wind speed was increased from 0 to 40 km hr^{-1}. Kimball (1973), on the other hand, found little or no correlation between wind speed and evaporation rate. In a later study, Hadas (1975) observed that cumulatuve evaporation from sieved aggregates decreased with environmental factors in the order wind > continuous radiation > intermittent radiation over a thirty day period.

Braunack (1979) related evaporation through aggregate beds (E) to pan evaporation (E_o), and by developing the equation

$$E/E_o = c + a(ps - pa) + ab.\ u(ps - pa) \qquad (6.2)$$

with a, b, and c being adjustable parameters. He found that wind speed (u) and the water vapour deficit (ps - pa) did not significantly affect E/E_o.

Gardner and Hillel (1962) found that the flow of heat has little influence on evaporation. Hanks, Gardner and Fairbourn (1967) demonstrated that computation of evaporation assuming isothermal conditions for a soil initially wet to near saturation would probably estimate total evaporation to within 10% error. They concluded that this was sufficiently accurate for many purposes. Hadas (1975), on the other hand, stressed that employing an isothermal equation of water flow to non-isothermal conditions can result in large errors.

The significance of thermally-induced flow during evaporation has also been pointed out by Wiegand and Taylor (1962) and Cary (1965; 1966). In order to calculate this flux, Cary (1965; 1966) developed the equations

$$J_v = -\eta \frac{D\ p\ H}{R^2\ T^3} \frac{d_T}{d_z} \tag{6.3}$$

and

$$J_l = \frac{k\ Q}{a\ T} \frac{d_T}{d_z} \tag{6.4}$$

where, J_v and J_l are vapour and liquid flux respectively, D is diffusivity, k is capillary conductivity, H is heat of evaporation, Q is liquid heat transport, R is the gas constant, T is temperature, and η is a factor accounting for pore geometry.

Using these equations, Cary (1966) tabulated the results of some earlier workers and showed that in saturated conditions the thermally-induced flow becomes more important as the hydraulic conductivity decreases. In unsaturated soils, the relative importance of thermally-induced flow rises rapidly as the soil water content decreases.

The aim of the experiments conducted here was to study the effects of tillage on soil water behaviour. The interest was not in the whole tilled soil, but only in the fluctuation of soil water in the tilled layer. Because of this, the term "drying" will be used to describe the loss of water (from this layer) instead of evaporation. In addition, the experiments were also designed to study the importance of meteorological factors in determining the rate of drying.

6.1.2 Materials and Methods

Soil water content fluctuations in tilled and untilled soils

Urrbrae red brown earth, with the properties described in section 3, was tilled with one pass of a tyne cultivator to a depth of about 10 cm in the Spring (Aug/Sept; Sept.Oct)1978, and in the Winter (June) 1979. To measure soil water content fluctuation, soil water content (of the tilled and untilled soil) was measured at 9.00 a.m. (to give the daily maximum soil water content as a result of wetting) and at 5.00 p.m. (to give the daily minimum soil water content as a result of drying) daily. These times were chosen in the light of the results of Ojeniyi (1978) which showed that soil water contents at these times were close to the daily maximum and minimum values.

Samples of about 50 g soil were collected from the 0-10 cm layer (6 samples at each time for the 1978 experiment, and 5 samples for the 1979 experiment), and the soil water content was determined gravimetrically. In addition, to study the variation in soil water content with depth in tilled soil, a further experiment was done in the Winter (July) 1979. In this experiment, the mean soil water contents were measured over the depth ranges of 0-5 cm and 5-10 cm.

The daily wetting and drying (Δ W) was found by summing up the changes in soil water content between 9.00 a.m. and 5.00 p.m., and between 5.00 p.m. and 9.00 a.m. on the following day. The cumulative wetting and drying was calculated from

$$\sum_t \Delta W = (|\Delta W_1|+|\Delta W_2|+|\Delta W_3|+ \ldots\ldots+|\Delta W_t|) - 2\, t(\frac{2\,S}{\sqrt{\pi n}}) \qquad (6.5)$$

where, the subscripts, 1, 2, 3 and t denote the amount of wetting and drying in day 1, day 2, day 3, and day t respectively. $\sum_t \Delta W$ is the cululative amount of wetting and drying between day 0 and day t, and $(\frac{2\,S}{\sqrt{\pi n}})$ is the estimated error resulting from summing differences between successive sub-samples of a normal population of soil water contents (see appendix).

The affect of meteorological factors on (daily) soil drying was analysed by the "Path analysis" theory developed by Wright (1921; 1923) and discussed by Tukey (1954). By doing this, not only the dependence of soil drying on meteorological factors can be discussed, but also the mutual association between these factors.

By taking the error into account, the daily amount of drying, Δd, of the 0-10 cm layer was calculated by

$$\Delta d = W_{9\ a.m.} - W_{5\ p.m.} - (\frac{2\,S}{\sqrt{\pi n}}) \qquad (6.6)$$

When the resulting $\Delta d < 0$, the drying was assumed to be zero. The meteorological data was found from the Waite Institute meteorological station (located at about 500 m from the experimental location).

Effect of tillage system on soil water behaviour

The experiment was carried out at the Mortlock experimental station of the Waite Institute in the Winter (June) 1980. The soil is a red brown earth with the properties described in section 3.1. The treatments were:

A_W. Minimum tillage : direct drilled with a combine drill fitted with 5 cm lucerne points (11/6 1980).

B_w. Minimum tillage : seeding with rotary seeder and compaction roller (6/6 1980).

C_w. Conventional tillage : cultivated with scarifier (29/4 1980), harrowed with heavy stump jump harrow (13/5 1980), cultivated with combine with 10 cm shares (21/5 1980, harrowed (26/5 1980), seeding with combine with 10 cm shares (10/6 1980).

D_2. Conventional tillage : tilled with Howard rotary hoe (30/4 1980 and 26/5 1980), seeding with rotary seeder and compaction roller (6/6 1980).

A_p. The plot carried pasture (the previous year this plot was cultivated as A_w).

D_p. The plot carried pasture (the previous year this plot was cultivated as D_w).

The subscripts w and p denote that when the experiment was carried out, the plot carried wheat (recently sown) and pasture respectively. A_p and D_p were considered to constitute non-tilled soil as there was little pasture cover on them.

Observations were started on 17/6/1980 and were completed on 26/6/1980. To study the daily variation water content, the measurements of soil water content was done at 8.00, 9.00, and 10.00 a.m.; and at 3.00, 4.00, and 5.00 p.m. Unlike in the previous experiment, soil water content was measured from samples from the 0-3 cm layer only.

6.1.3 Results and Discussion

Soil water content fluctuations

It was found that the fluctuation of soil water content in the tilled plots was much higher than that in the non-tilled plots. Thus the tilled plots wetted and dried more intensively than non-tilled

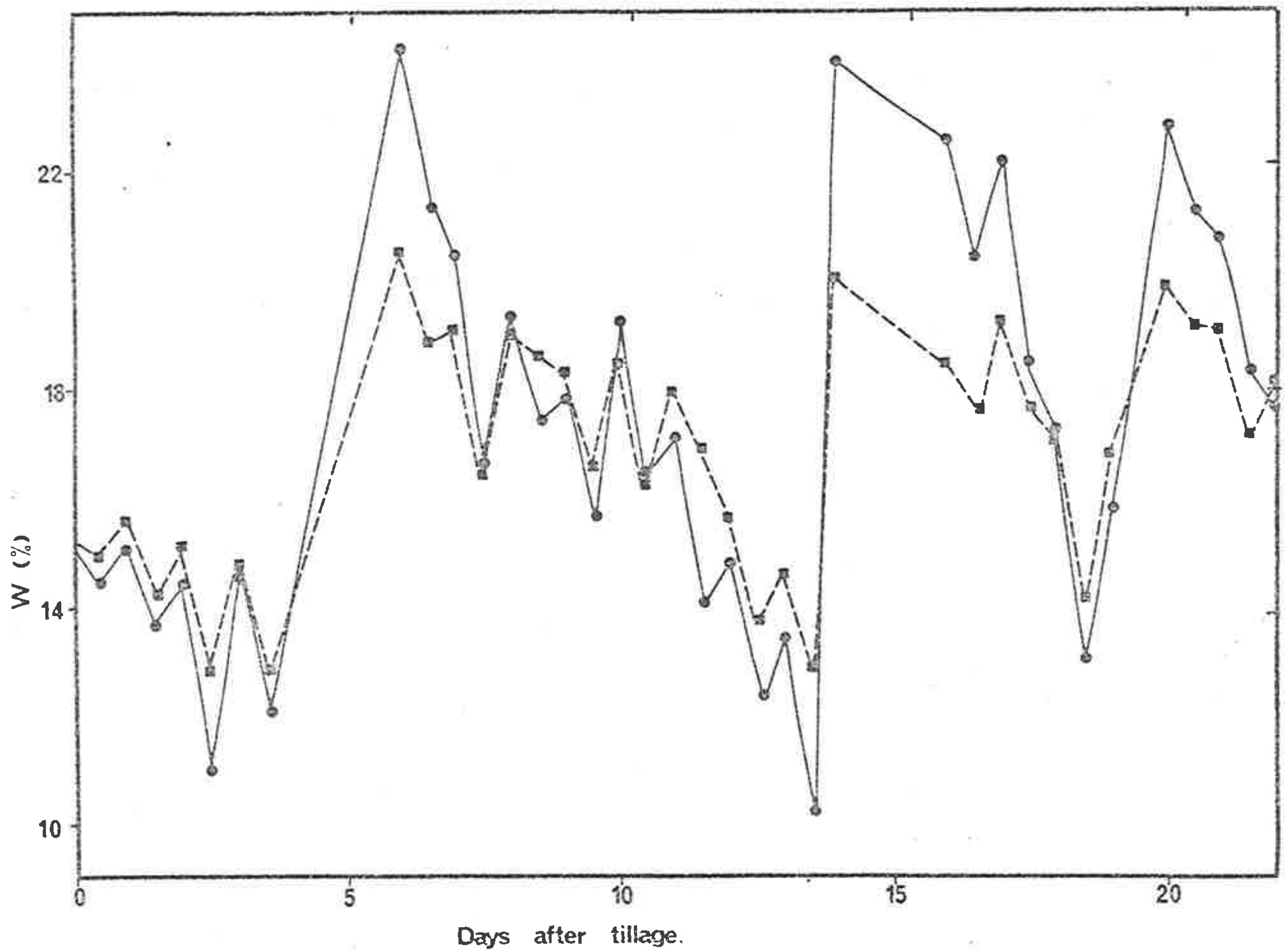


Fig. 6.1. Soil water content fluctuations of tilled (●) and non-tilled (■) plots.
Exp. 1 1978 (29/8 - 20/9 1978).

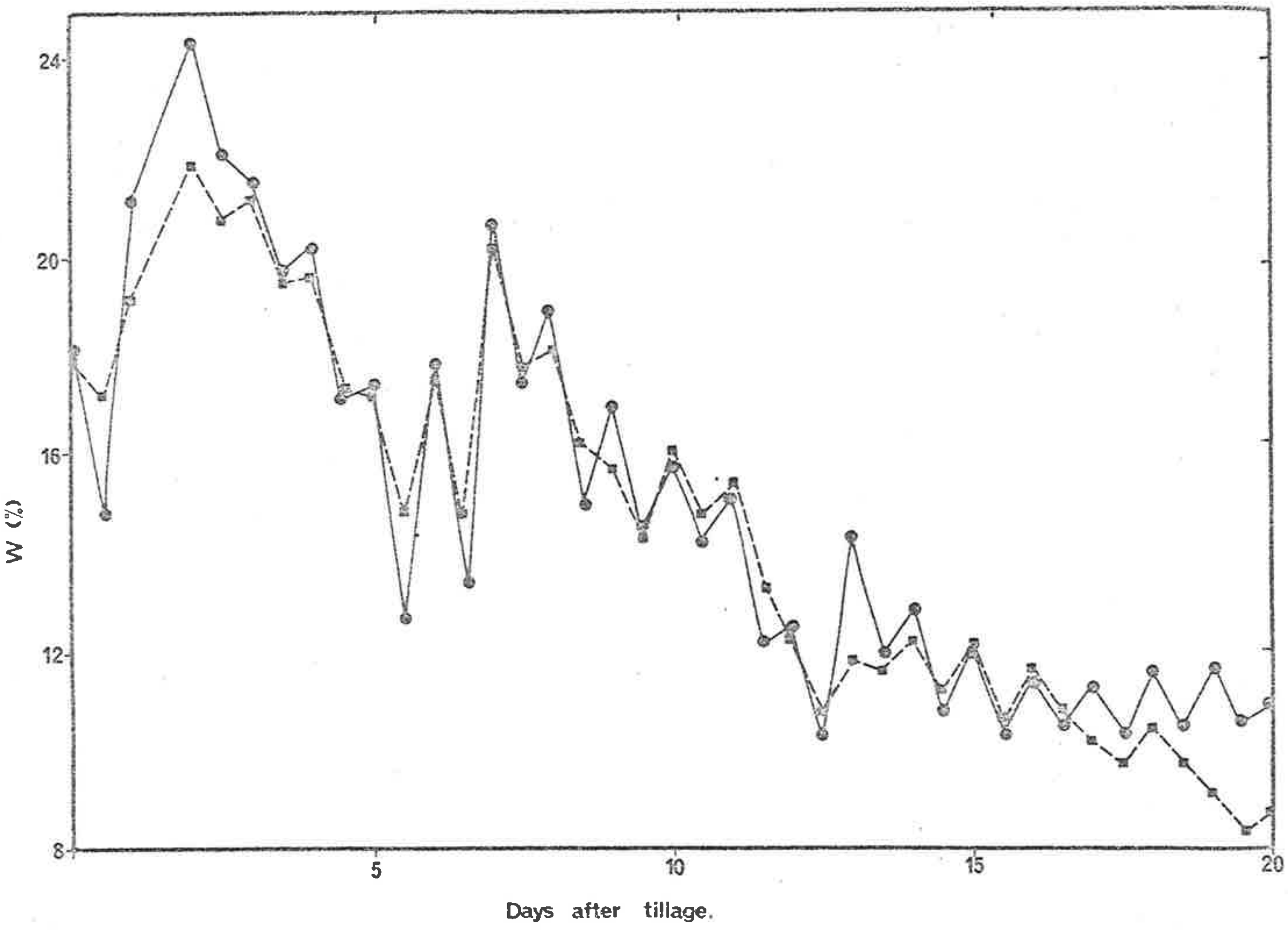


Fig. 6.2. Soil water content fluctuations of tilled (●) and non-tilled (■) plots.
Exp. 2, 1978 (20/9 - 10/10 1978).

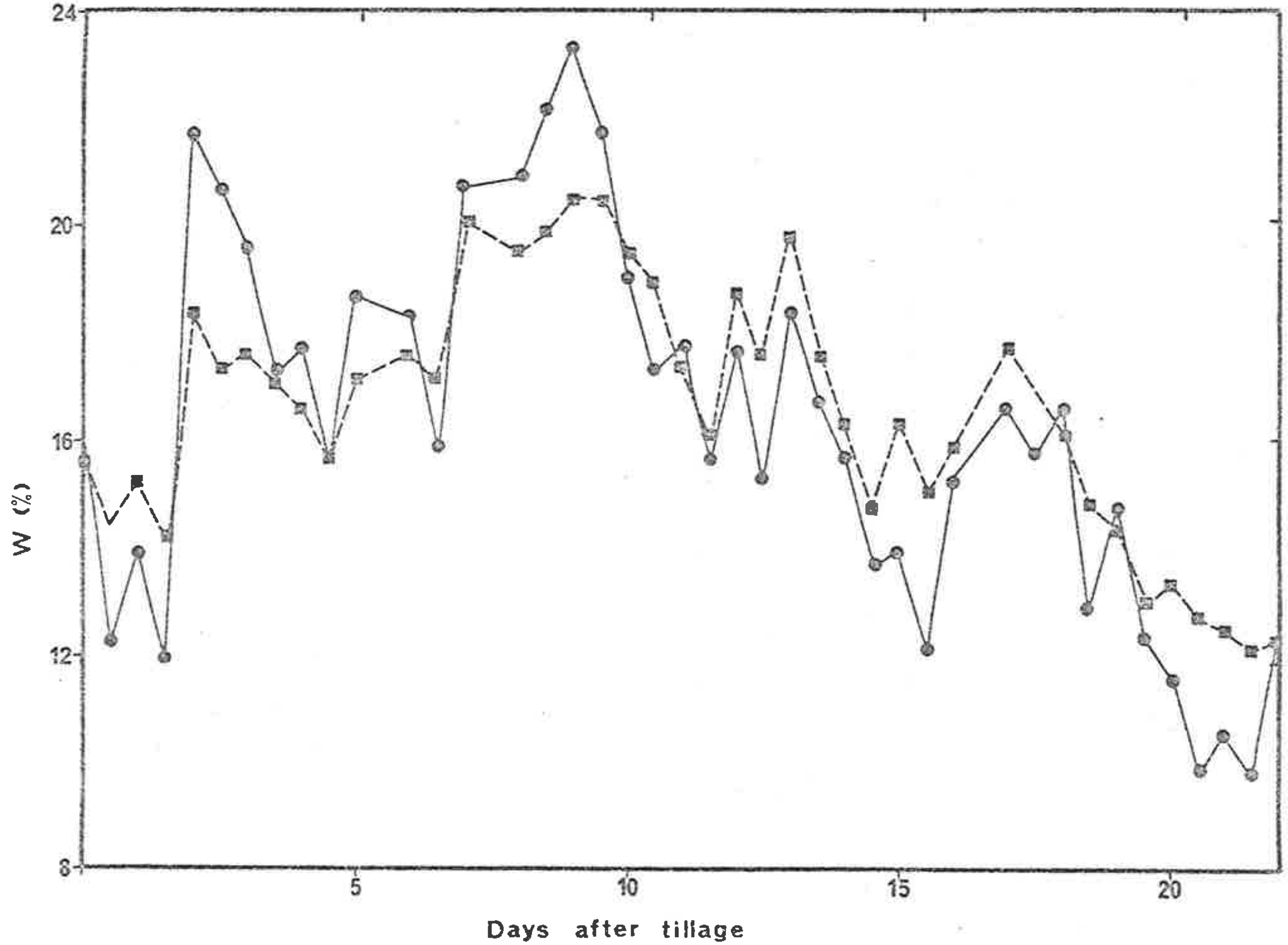


Fig. 6.3. Soil water content fluctuations of tilled (●) and non-tilled (■) plots.
Exp. 3 (6/6-28/6/79)

plots (Figure 6.1, 6.2, and 6.3). As a result, the cumulative wetting and drying in the tilled plots was much greater than that in the non-tilled plots. Up to 20 days after tillage the cumulative wetting and drying in the tilled plot was 1.79, 1.78, and 2.09 times greater than of the non-tilled plot for the 1978 (experiment 1), 1978 (experiment 2), and 1979 experiment respectively.

The greater cumulative wetting and drying in the tilled plots can also be seen from the slope (b) value of equation

$$\sum_{t} \Delta W = B + b\,t \qquad (6.7)$$

obtained by plotting the cumulative wetting and drying against time, t (in days), after tillage (Table 6.1, Figures 6.4, 6.5, and 6.6).

Table 6.1. Values of B and the b parameters and coefficient of determination of equation (6.7) obtained from the tilled (TL) and non-tilled (NTL) plots.

Experiment	B		b		r^2	
(year)	TL	NTL	TL	NTL	TL	NTL
1978 (1)	-4.05	-1.94	4.03	2.26	0.99	0.99
1978 (2)	10.26	3.01	3.15	2.07	0.93	0.94
1979	6.92	0.55	2.43	1.30	0.98	0.96

The greater amount of wetting in the tilled plots was more significant after rainy days. Because of the greater porosity in the tilled soil, the rate of infiltration, as well as the amount of water which can be stored is greater than that in the non-tilled plot. In these experiments (Figure 6.1, 6.2, and 6.3) the maximum soil water content (after rainy days) observed was around 25% (in the tilled plot)

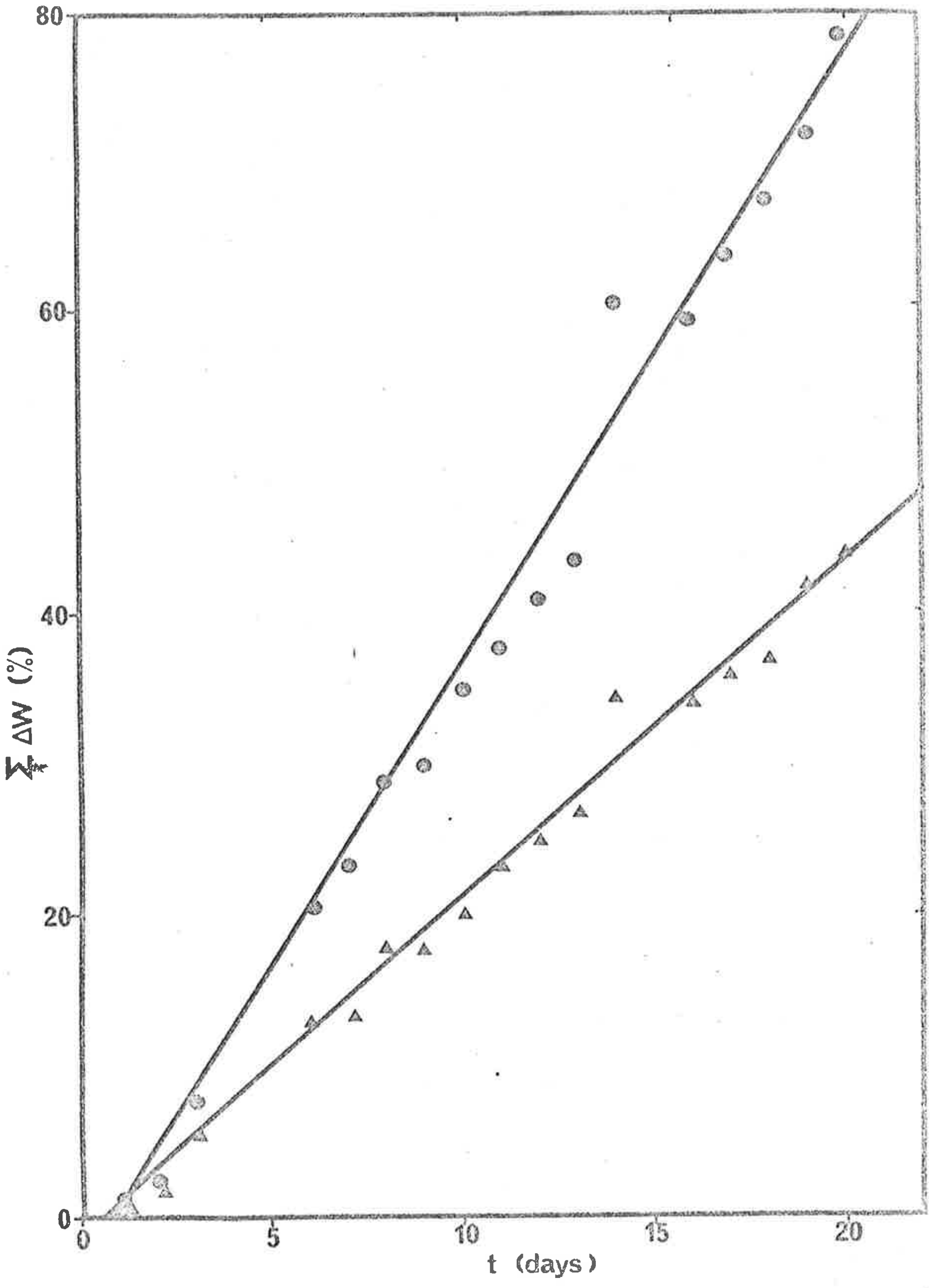


Fig. 6.4. Cumulative wetting and drying, Σ Δ W, (as a function of time, t, after tillage) of tilled (●) and non-tilled (▲) plots (1978 exp. 1).

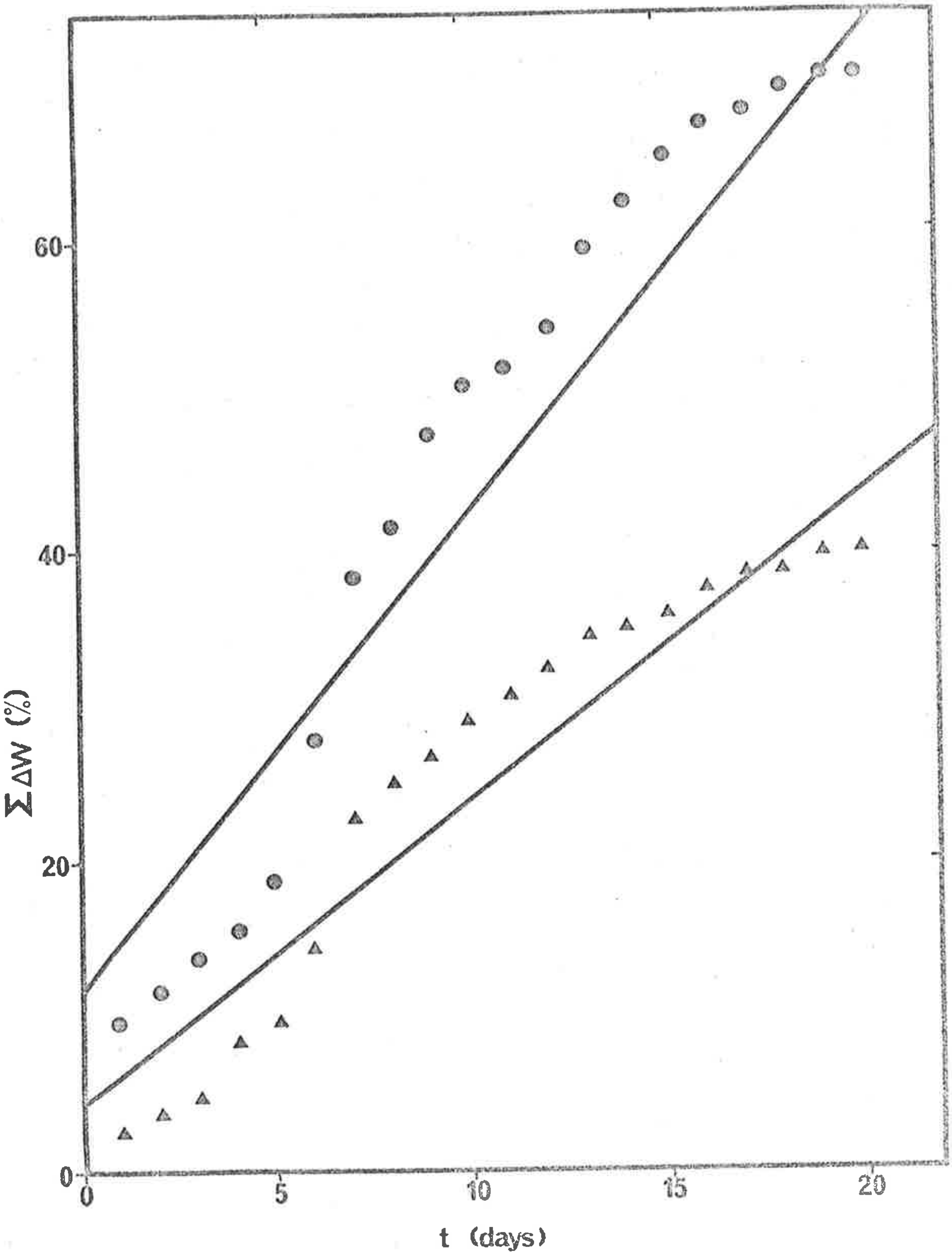


Fig. 6.5. Cumulative wetting and drying, Σ Δ W, (as a function of time, t, after tillage) of tilled (●) and non-tilled (▲) plots (1978, exp. 2).

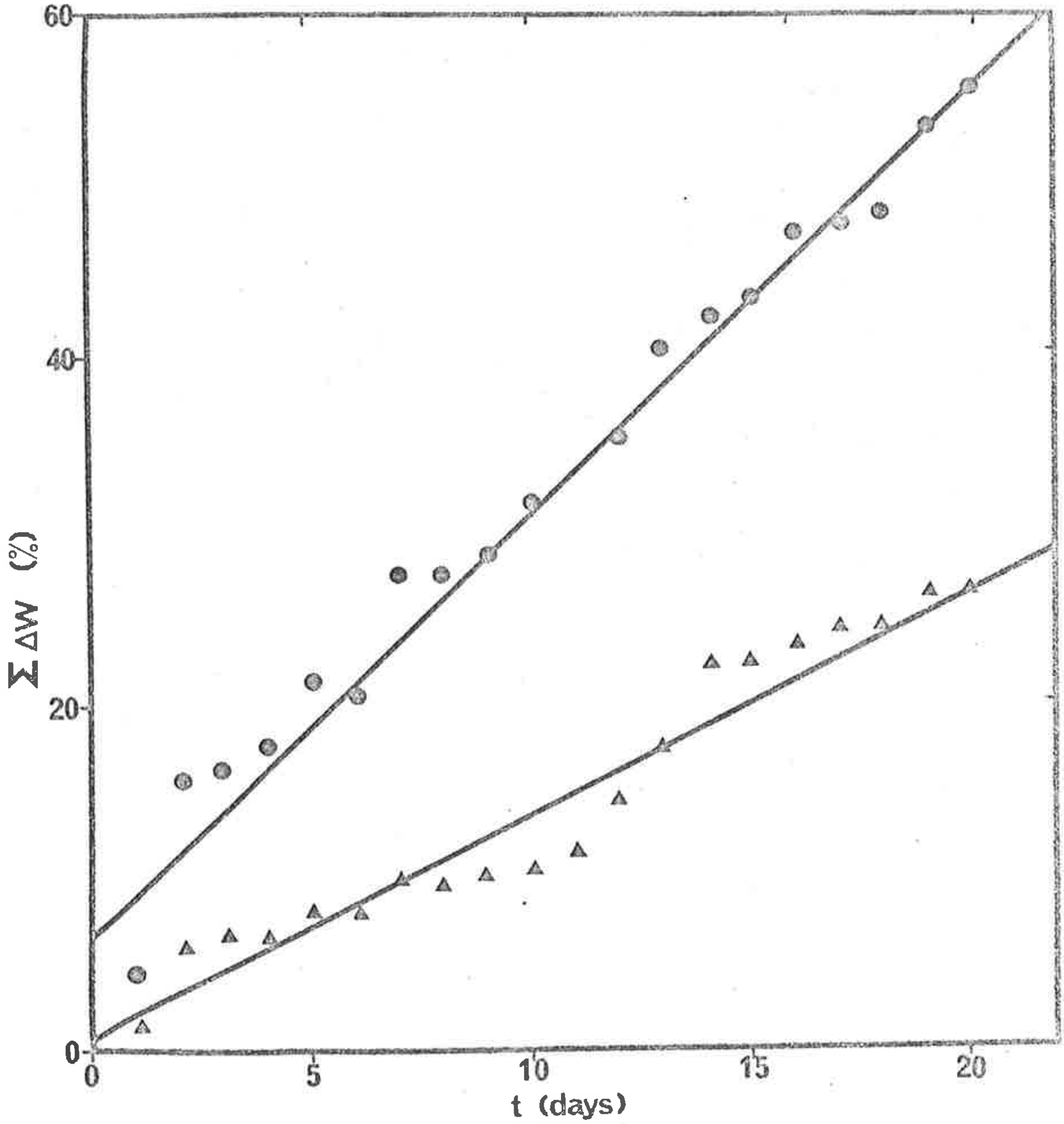


Fig. 6.6. Cumulative wetting and drying, $\Sigma \Delta W$, (as a function of time, t, after tillage) of tilled (●) and non-tilled (▲) plots, 1979 exp.

and 21% (in the non-tilled plot). The increase in the potential storage capacity due to tillage has also been found by some Russian workers (van Duin, 1955).

The tilled plot not only had a greater total porosity but also had larger pores. The importance of pore size distribution in determining the rate of infiltration has been well established by Marshall (1958). By his classical equation, Marshall (1958) demonstrated that hydraulic conductivity and hence infiltration rate of a soil increases with increasing void volume and size, and with the degree of soil saturation.

In addition, the increase in surface roughness due to tillage (Burwell *et al.*,1966; Allmaras *et al.*,1977; Dexter, 1977) can influence surface detention of water. By increasing the time available for infiltration, this surface roughness significantly increases infiltration. Burwell *et al.*(1965) have shown that a soil which has been ploughed with porosity fraction of 0.66 and random roughness of 4.98 cm had a cumulative water intake (prior to run off) of 17.2 mm, whereas non-tilled soil with porosity fraction of 0.53 and random roughness of 0.76 cm had only 0.89 mm. Greater infiltration due to the increase in the surface roughness has also been found by Johnson *et al.*(1979). There was some run-off from the non-tilled, but not the tilled, plots in the 1978 and 1979 experiments reported here.

It can be seen in Figures 6.1, 6.2, and 6.3, that even on days with no rain, the rate of wetting in the tilled plots was still greater than in the non-tilled plots. This was probably due to the higher water content of the deeper layers of the tilled plots. Because of the higher infiltration, the layer beneath the tilled layer stores a larger amount of water than that of the same (depth) layer beneath a non-tilled top soil. The higher water content in this layer may also result from downward movement of water from the tilled layer during the hottest part of the day. This downward movement is caused by the temperature gradient (Gurr, Marshall and Hutton, 1952; Ojeniyi, 1978). Gurr *et al.* (1952) suggested that the maximum net water movement is toward the cooler temperature. Temperature of a tilled soil, during the day, decreases with depth (Allmaras *et al.*, 1977; Ojeniyi, 1978). Though the temperature in non-tilled soil also decreases with depth, it seems that due to the modification of the heat flux (de Vries, 1963; Hadas, 1975) and the net radiation (Allmaras, 1967), the temperature gradient in the tilled soil is greater than that in non-tilled soil. So, it is reasonable to assume that any downward movement of soil water in the tilled soil is greater than that in non-tilled soil.

At night, the temperature of the surface layer decreases. Also, matric water potential at the surface is more negative than it is deeper down. Thus, water flows upwards for two reasons. Since the flux of water is proportional to the potential gradient, and because of the potential gradient in the tilled soil is higher than that in non-tilled soil, it is, therefore reasonable to suggest that the tilled soil will wet more rapidly than non-tilled soil. In addition, because the surface of the tilled plot gets colder at night (van Duin, 1954), it will attract more condensation (dew) water from the atmosphere, and this factor can also contribute to this greater wetting rate.

The greater drying rate of the tilled layer found in this experiment is not necessarily in contradiction with the results of evaporation experiments done by some earlier workers (Willis, 1960; Hillel and Hadas, 1972). As discussed previously, the data found in these experiments just showed the water loss from the tilled layer, not the total loss from the soil. The data of those workers was obtained from a laboratory study in the presence of water table, and thus showed the total loss of water from the soil (water table).

Gardner (1958) has shown that the maximum evaporation rate is related to the soil hydraulic conductivity and the depth of the water table. Holmes Greacen and Gurr, (1960) have reported that the water table of the Urrbrae red brown earth is at about 30 m depth, and that there is no capillary rise from this water table to the soil surface. Under these conditions, the influence of the water table can be ignored. The rate of drying in these experiments, therefore, is mainly related to the soil unsaturated hydraulic conductivity.

There is no doubt that tillage modifies pore size and pore arrangement, and hence hydraulic conductivity. In an attempt to reduce evaporation from a tilled soil, several workers (Holmes *et al.*, 1960; Hillel and Hadas, 1972; Kimball, 1973; Hadas, 1975; Braunack, 1979) have studied the effect of aggregate size on evaporation. They found that a minimum evaporation occurs through beds of aggregates of 1.0 - 2.0 mm diameter. In these experiments, the first implement pass produced more than 60% (1978 experiment) and more than 50% (1979 experiment) aggregates with diameters larger than 9.5 mm. It has been found that there is a greater penetration of turbulent air currents into larger interaggregate pores (Hanks and Woodruff, 1958; Holmes *et al.*, 1960). As a result, evaporative water loss is correspondingly higher. Holmes *et al.* (1960) found that the evaporation rate from a seed bed with clods of 25.0 - 50 mm diameter was as high as 2.4 times that from non-tilled soil.

In addition, the downward movement of water due to the midday temperature gradient, as has been suggested, may also contribute to this greater water loss from the surface soil. Because of the higher net radiation (Allmaras *et al.*, 1977) and smaller heat flux (de Vries, 1963; Allmaras *et al.*, 1977) the surface of a tilled soil has a higher temperature than that of non-tilled soil. This means that tillage increases the temperature gradient between the surface and the sub-soil. Hay (1977) found that except for a very cool day (air temperature below 4^{o}C) the temperature gradient (with depth) in tilled soil is relatively high compared to that in non-tilled soil. As a consequence of this temperature increase, the thermally-induced flow in tilled soil is more significant than that in non-tilled soil. The significance of water flow due to temperature gradients in influencing evaporation has been pointed out by several workers (Gurr *et al.*, 1952; Wiegand and Taylor, 1962; Cary, 1965; Cary, 1966). Cary (1965) found that a temperature gradient of 0.5^{o}C/cm at a matric water potential of -6.7 kPa would move as much as water through the soil as a water potential gradient of 0.2 kPa per cm. Joshua and de Jong (1973) observed that a temperature gradient smaller than 1.6^{o}/cm had a significant effect on water content in a fine sandy loam soil. Ojeniyi (1978) has shown that a temperature difference as large as 5^{o}C can exist between the 5 and 10 cm depths in a coarsely-tilled soil.

As expected, the intensity of wetting and drying in the 5-10 cm layer of the tilled plot was much lower than that in 0-5 cm layer (Figure 6.7). Fitting this data to equation (6.7) resulted in the B and b values given in Table 6.2. It is necessary to point out that the results for the soil with very small soil water content fluctuation (such as in the 5-10 cm layer) are meaningless for the first few days, because they predict $\sum_{t} \Delta W$ being negative. This occurs because the standard deviation (S, in equation 6.5) is much greater than the soil water content changes. As Shown in Figure 6.8 the cumulative water content change is negative when t less than 3 days. This tendency can also be seen in the result in Figure 6.4.

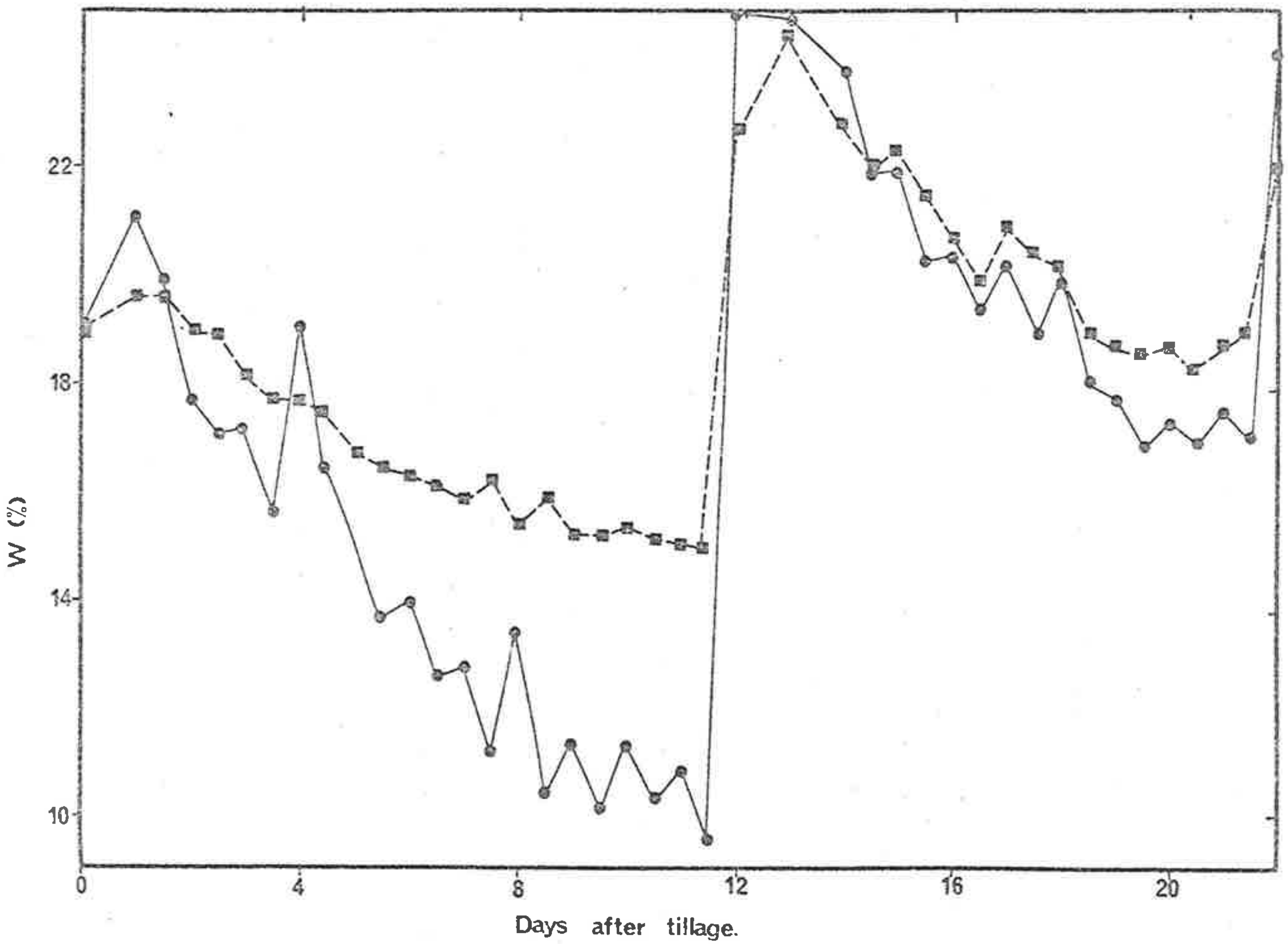


Fig. 6.7. Soil water content fluctuations of 0 - 5 (●) and 5 - 10 cm (■) layers of a tilled plot.

Table 6.2. Values B and b parameters, and coefficient of determination of equation (6.7) found from 0-5 cm and 5-10 cm layer of the tilled plot.

Layer depth (cm)	B	b	r^2
0 - 5	2.11	2.17	0.94
5 - 10	-3.23	1.08	0.94

The ratio of the cumulative wetting and drying in the 0-5 cm layer to that in the 5-10 cm layer in the first 4 days was 10.81. For a longer time this ratio decreased due to a high wetting rate in the 5-10 cm layer caused by rainfall. Until 20 days after tillage, this ratio was only 2.02.

The greater soil water content of the 5-10 cm layer compared to that of the 0-5 cm layer is reasonable. This occurs due to the continuous replenishment that occurs from the stored water in the undisturbed soil underlying the tilled layer. In addition, any downward movement of water from the top tilled layer as discussed above would also contribute to this larger value of soil water content.

Effect of tillage system on soil water behaviour

The mean water contents of the A_W treatment at 8.00, 9.00, and 10.00 a.m., and at 3.00, 4.00, and 5.00 p.m. were 25.44%, 25.43%, 24.22% and 20.23%, 19.30% and 18.93% respectively. For the D_W treatment, the corresponding mean water contents were 23.06%, 22.94%, 22.18% and 17.82%, 17.59% and 17.50%. The effects of tillage systems on the mean soil water contents at 9.00 a.m. and at 5.00 p.m. are given in Table 6.3.

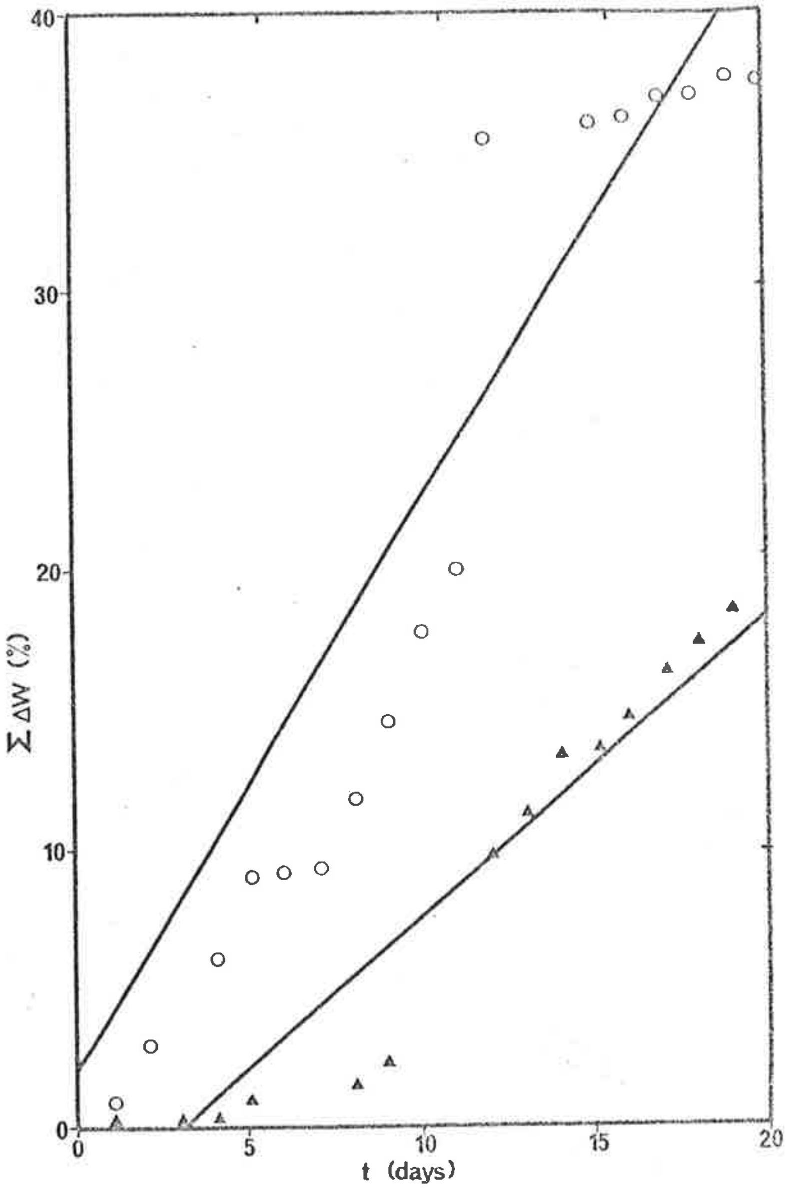


Fig. 6.8. Cumulative wetting and drying, $\Sigma \Delta W$, (as a function of time, t, after tillage) of 0 - 5 cm (○) and 5 - 10 cm (▲) layers of a tilled plot.

Table 6.3. The mean soil water content as influenced by tillage system.

Treatment	Water content (%) at	
	9.00 a.m.	5.00 p.m.
A_w	25.43	18.91
D_w	22.70	18.57
C_w	24.47	19.93
D_w	22.76	17.50
A_p	25.83	24.75
D_p	24.78	23.40

The results in Table 6.3 show that in the non-tilled plots (A_p and D_p) the difference in mean soil water content between at 9.00 a.m. and 5.00 p.m., is very small. This value is much smaller than that obtained in tilled plots (A_w, B_w, C_w, and D_w). For the first 10 days of observation, the cumulative wetting and drying in the A_w, B_w, C_w and D_w treatments was greater by a factor of 5.65, 3.12, 3.43 and 4.51 compared to that in the non-tilled treatment (means of A_p and D_p treatments).

Influence of meteorological factors on soil drying

Before discussing the effect of meteorological factors on drying rate, it is interesting to discuss the relationship between evaporation from a soil (drying) and the potential evaporation. The potential evaporation was obtained from "pan evaporation" data from the Waite Institute meteorological station. These data were subjected to correlation analysis, and the values of the Pearson's linear coefficient of correlation

$$r_{ij} = \frac{\text{cov. } (x_i . x_j)}{\sqrt{\text{var } (x_i) \text{ var } (x_j)}} \qquad (6.8)$$

were calculated.

The result (Table 6.4) shows that there was a significant correlation between both the drying from the tilled layer of the tilled plot and the same (depth) layer of the non-tilled plot with pan evaporation. This indicates, that as evaporation from a water surface (pan evaporation), meteorological factors have an important effect in determining the rate of drying from both tilled and non-tilled soil.

Table 6.4. The coefficient of correlation (r) and covariance (cov) obtained from the relationship between the soil drying with pan evaporation.

Experiment (year)	r		cov.	
	Tilled	Non-tilled	Tilled	Non-tilled
1978 (1)	0.56*	0.60*	0.57	0.50
1978 (2)	0.66*	0.64*	0.78	0.45
1979	0.49*	0.44*	0.33	0.12

* Significance

The importance of radiant energy as a source of evaporation energy is well known (Penman, 1948; Hadas, 1975). Temperature, wind speed, and relative humidity have all been found to be factors significantly influencing evaporation from soil (Holmes *et al.*, 1960; Hadas, 1975; Braunack, 1979).

In addition, based on the Lemon's (1956) discussion, it is reasonable to think that the initial soil water content must be considered as the most important factor which determines the rate of water loss from a soil.

To study the relative importance of these factors, a path analysis was applied. In the path diagram, double arrowed lines indicate the mutual association between the independent variables as measured by coefficients of correlation, r_{ij}, and the single arrowed lines represent direct influences of independent variables to dependent variables as measured by "path coefficients", P_{iy}. The residual variables, R_x, are assumed to be independent of the remaining variables.

For constructing the path diagram, the Pearson's linear coefficient of correlation within the independent variables was formed into the correlation matrix

$$C = \begin{vmatrix} r_{11} & r_{12} & r_{13} & \cdots\cdots & r_{1n} \\ & r_{22} & r_{23} & \cdots\cdots & r_{2n} \\ & & r_{33} & & r_{3n} \\ & & & \cdots\cdots & \\ & & & & r_{nn} \end{vmatrix} \qquad (6.9)$$

and the coefficients of correlation between the independent variables and the dependent variables r_{iy}, were formed into the matrix

$$B = \begin{vmatrix} r_{1y} \\ r_{2y} \\ r_{3y} \\ \cdots \\ . \\ r_{ny} \end{vmatrix} \qquad (6.10)$$

The path coefficients, P_{iy}, were obtained from

$$P_{iy} = C_o B \qquad (6.11)$$

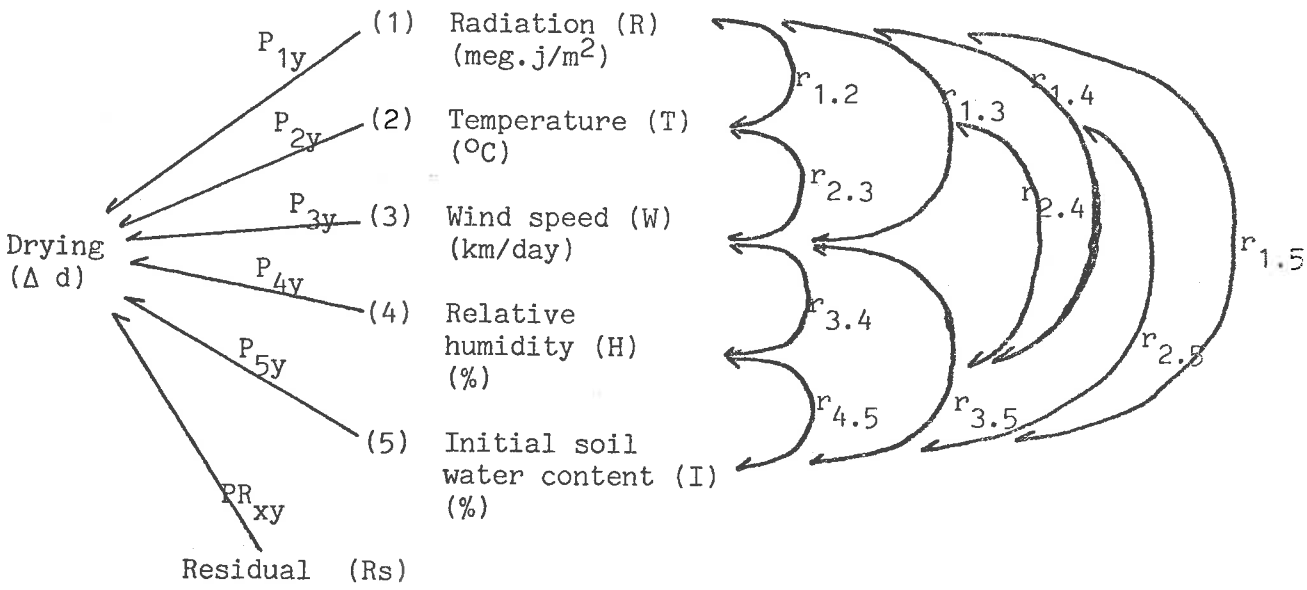
where C_o was the matrix obtained by deleting the matrix C.

The residual direct effect, P_{Rxy}, was found from

$$1 = r_{1y}P_{1y} + r_{2y}P_{2y} + r_{3y}P_{3y} \ldots\ldots + r_{ny}P_{ny} + P^2_{Rxy} \qquad (6.12)$$

For this analysis, the temperature used was the daily maximum temperature (^{o}C). The temperature and wind speed (km/day) data used were the surface temperature and pan wind speed.

The path diagram proposed was



The correlation matrix of observed variables for the 1978 (experiment 1) is given in Table 6.5. Temperature (T) and relative humidity (R) are the only meteorological factors which correlated significantly with drying both from tilled and non-tilled plots. Radiation was significantly correlated with drying only from the non-tilled plots. It can be seen from the values of the correlation coefficients (Table 6.5) that the rate of drying decreases with increasing temperature and radiation, and decreasing relative humidity. This is explainable. The increase in radiation and temperature could be expected to result in a greater drying energy, and hence water loss itself. The

Table 6.5. Correlation matrix of observed variables for the 1978 experiment 1.

Kinds of variables	R	T	W	H	I TL	I NTL	Drying rate (r_{iy}) TL	Drying rate (r_{iy}) NTL
R	-	0.12	-0.33	-0.36	-0.09	-0.12	0.26	0.44*
T		-	0.39	-0.77*	-0.71*	-0.74*	0.59*	0.61*
W			-	-0.20	-0.20	-0.23	0.23	0.21
H				-	0.72*	0.75*	-0.51*	-0.59*
I					-	-	-0.38	-0.28

* significant at the probability of 5%.

decrease in relative humidity results in an increase in the tendency of soil water to move to the air.

There was a tendency for a decrease in water loss to be associated with increasing initial water content as can be seen from the negative correlation coefficients (r = -0.38 and r = -0.28, for the tilled and non-tilled plot respectively). Actually the increase in soil water content resulted in an increase in drying rate as shown by the positive path coefficient (Table 6.6, Figure 6.9), but due to the occurrence of positive correlation between initial soil water content with relative humidity (r = 0.72), which in turn was negatively correlated with drying both from the tilled (r = -0.51) and non-tilled plots (r = -0.59), and negative correlation between initial soil water content and temperature (r = -0.71), which positively correlated with drying (r = 0.59 and r = 0.61), the net result is negative. The path coefficient (Table 6.6) shows that this negative value originated from its indirect effect through temperature, relative humidity, radiation and wind speed.

Table 6.6 Path coefficient of observed variables upon drying rate from tilled and non-tilled plots (1978-1).

Plot	Via	Drying versus R	T	W	H	I
Tilled plot	R	0.21[1]	0.03	-0.07	-0.08	-0.02
	T	0.06	0.54	0.21	-0.41	-0.38
	W	-0.03	0.03	0.09	-0.02	-0.02
	H	0.02	0.05	0.01	-0.06	-0.04
	I	0.00	-0.06	-0.01	0.06	0.08
	r_{iy}	0.26	0.59	0.23	-0.51	-0.38
Non-tilled plot	R	0.35	0.04	-0.12	-0.12	-0.04
	T	0.08	0.65	0.25	-0.50	-0.48
	W	-0.04	0.05	0.13	-0.02	-0.03
	H	0.11	0.25	0.07	-0.33	-0.24
	I	-0.06	-0.38	-0.12	0.38	0.51
	r_{iy}	0.44	0.61	0.21	-0.59	-0.28

[1] direct effect

Although relative humidity was significantly correlated with drying, its direct effect on drying was very small, even smaller than the direct effect of wind speed (for the tilled plot) which was not significantly correlated with drying. This occurs because almost all of the relative humidity effect was indirect via temperature (-0.41 for the tilled plot, and -0.50 for the non-tilled plot). It can be seen from the path coefficient value (Table 6.6, Figure 6.9) that temperature and radiant energy were the most important factors influencing the drying from both the tilled and non-tilled plots.

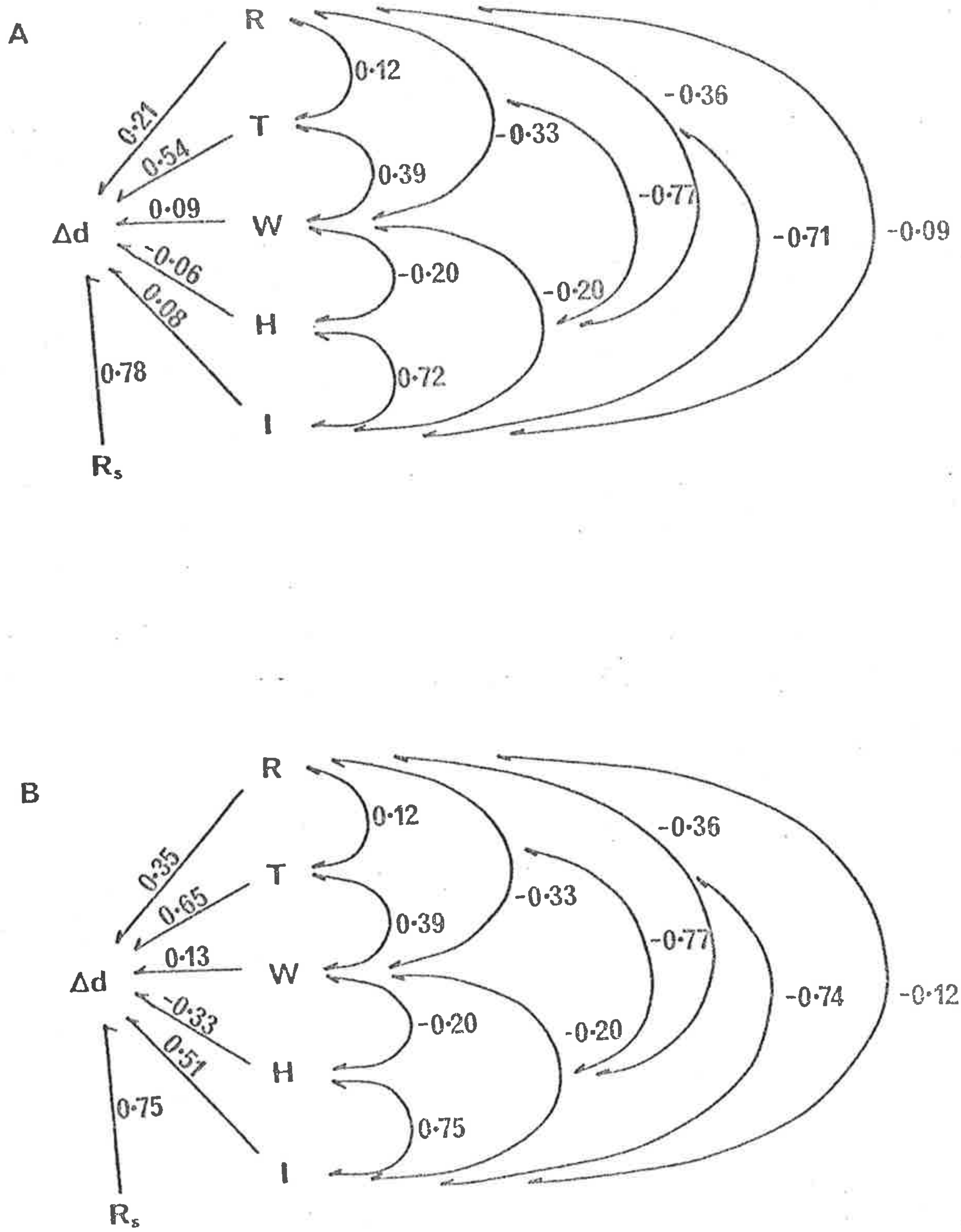


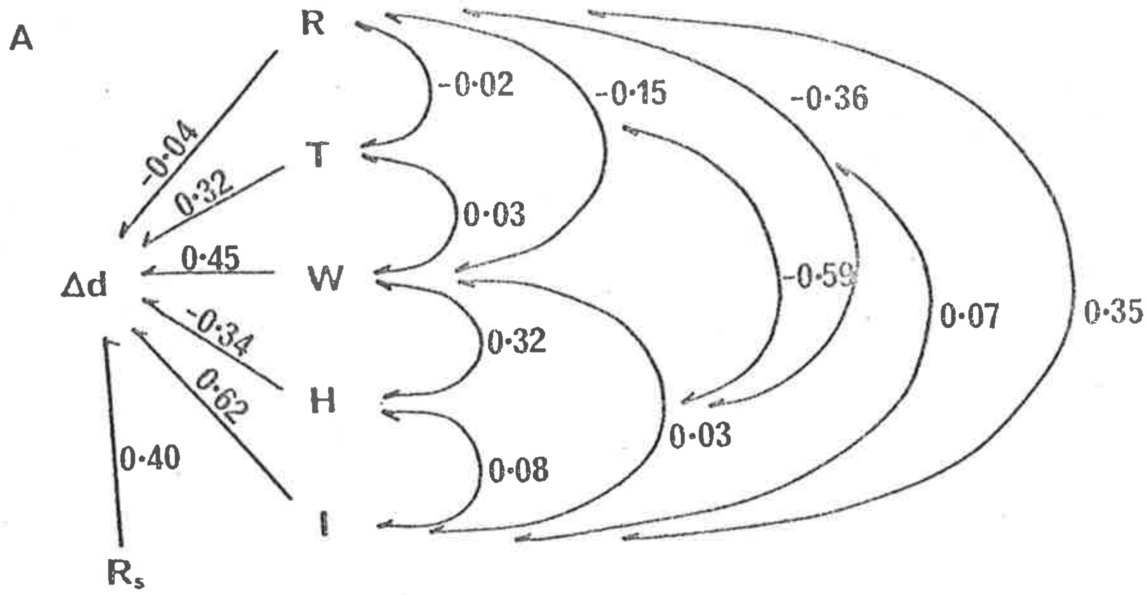
Fig. 6.9. Path diagram of the effect of meteorological factors and initial soil water content on drying rate from tilled (A) and non-tilled (B) plots (1978, exp. 1).

The result of the second experiment which was conducted in the late Spring 1978 (Table 6.7) shows that the only meteorological factor which was significantly correlated with drying both from the tilled and non-tilled plots was temperature (r = 0.58 and r = 0.68). It is interesting to notice that in this experiment, the initial soil water content was the most important factor determining drying rate, as can be seen from both the coefficient of correlation (Table 6.7) and path coefficient (Table 6.8 and Figure 6.10). It can be thought that the second stage of drying as discussed by Lemon (1956) existed in this experiment. From Figures 6.1 and 6.2 it can be seen that the initial soil water content in this experiment was mostly smaller than that in the previous experiment. In the previous experiment (Figure 6.1) the smaller initial water content was around 15%, whereas in this experiment (Figure 6.2) it was around 10%. Thus it can be suggested that when the soil water content of the Urrbrae red brown earth was around 10% or lower, the second stage of drying occurs.

Table 6.7. Corrleation matrix of observed variables for the 1978 experiment 2.

Kinds of variables	R	T	W	H	I		Drying (r_{iy})	
					TL	NTL	TL	NTL
R	-	-0.02	-0.15	-0.36	0.35	0.38	0.22	0.11
T		-	0.03	-0.59*	0.07	0.20	0.58*	0.68*
W			-	0.32	0.03	0.02	0.38	0.29
H				-	0.08	-0.02	-0.32	-0.11
I					-	-	0.61*	0.61*

* significant at the probability of 5%.



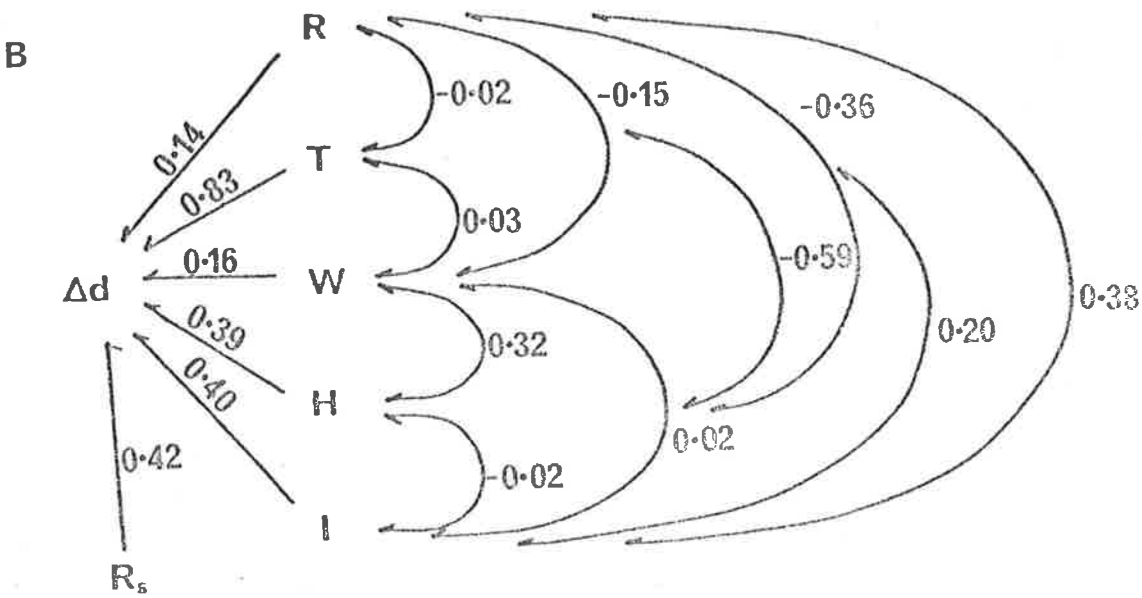


Fig. 6.10. Path diagram of the effect of meteorological factors and initial soil water content on drying rate from tilled (A) and non-tilled (B) plots (1978 exp. 2).

Table 6.8. Path coefficient of observed variables upon drying rate from tilled and non-tilled plot (1978 -2).

Plot	Via	Drying versus R	T	W	H	I
Tilled plot	R	-0.04[1]	0.01	0.01	0.01	-0.01
	T	-0.01	0.32	0.01	-0.18	0.02
	W	-0.07	0.01	0.45	0.13	0.01
	H	0.12	0.20	-0.11	-0.34	-0.03
	I	0.22	0.04	0.02	0.06	0.62
	r_{iy}	0.22	0.58	0.38	-0.32	0.61
Non-tilled plot	R	0.14	-0.00	-0.02	-0.05	0.05
	T	-0.02	0.83	0.02	-0.49	0.17
	W	-0.02	0.00	0.16	0.05	0.00
	H	-0.14	-0.23	0.12	0.39	-0.01
	I	0.15	0.08	0.01	-0.01	0.40
	r_{iy}	0.11	0.68	0.29	-0.11	0.61

[1] direct effect

Unlike in the previous experiment, relative humidity was not significantly correlated with drying. It seems that the initial water content was too small to be influenced by relative humidity (r = 0.08 and r = -0.02 for the tilled and non-tilled plots respectively). As a consequence, the drying was less influenced by relative humidity.

In the Winter 1979, radiation and temperature were not significantly correlated with drying either from the tilled or the non-tilled plots (Table 6.9). It is likely that radiation and temperature were too low to influence soil drying. In this season, wind speed was an important factor

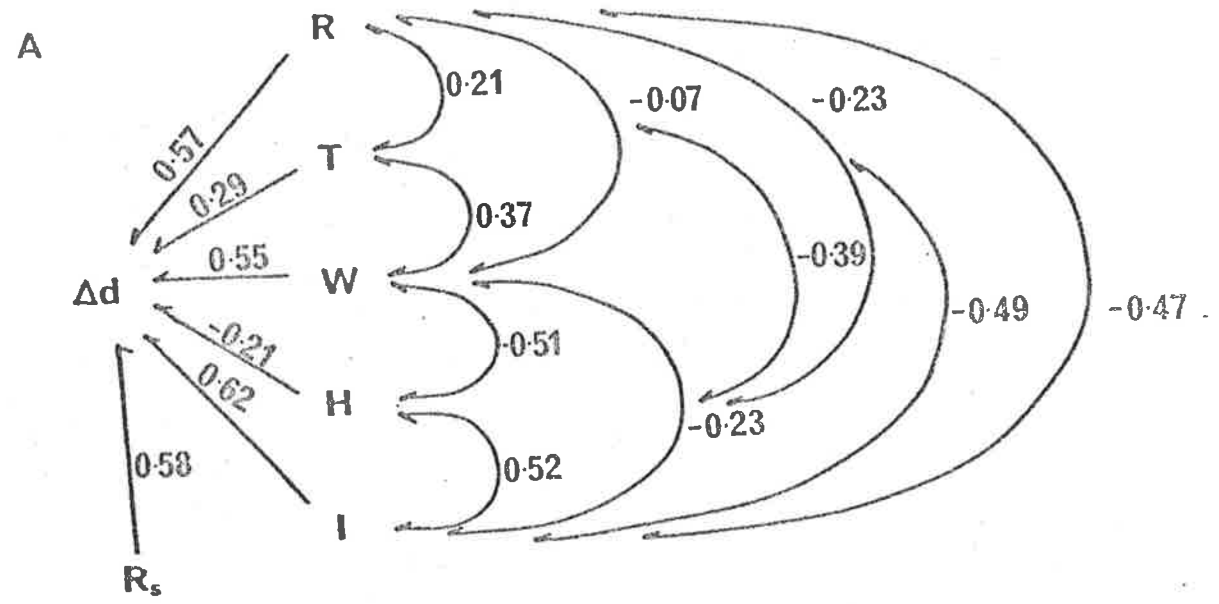
Table 6.9. Correlation matrix of observed variables for the 1979 experiment.

Kinds of variables	R	T	W	H	I TL	I NTL	Drying (r_{iy}) TL	Drying (r_{iy}) NTL
R	-	0.21	-0.07	-0.23	-0.47*	-0.26	0.36	0.31
T		-	0.37	-0.39	-0.49*	-0.54*	0.36	0.21
W			-	-0.51*	-0.23	-0.20	0.49*	0.37
H				-	0.52*	0.52*	-0.38	-0.43
I					-	-	-0.01	0.15

* significant at the probability of 5%.

as can be seen from correlation coefficient (Table 6.9) and path coefficient (Table 6.10 and Figure 6.11). As in the second experiment of 1978, relative humidity was not significantly correlated with soil water loss from the top 10 cm layer, and the initial soil water content was the most important factor determining this water loss.

From the results discussed above, it can be concluded (as suggested by Lemon, 1956) that when soil water content is high enough to meet evaporation demand, the rate of drying was chiefly controlled by meteorological factors (1978 experiment 1). In this condition, the initial soil water content did not significantly influence drying rate. As the soil water content decreased to a value at which the second stage of drying occurs (for the Urrbrae red brown earth this was around 10%), the dominance of these meteorological factors was replaced by the dominance of the initial soil water content.



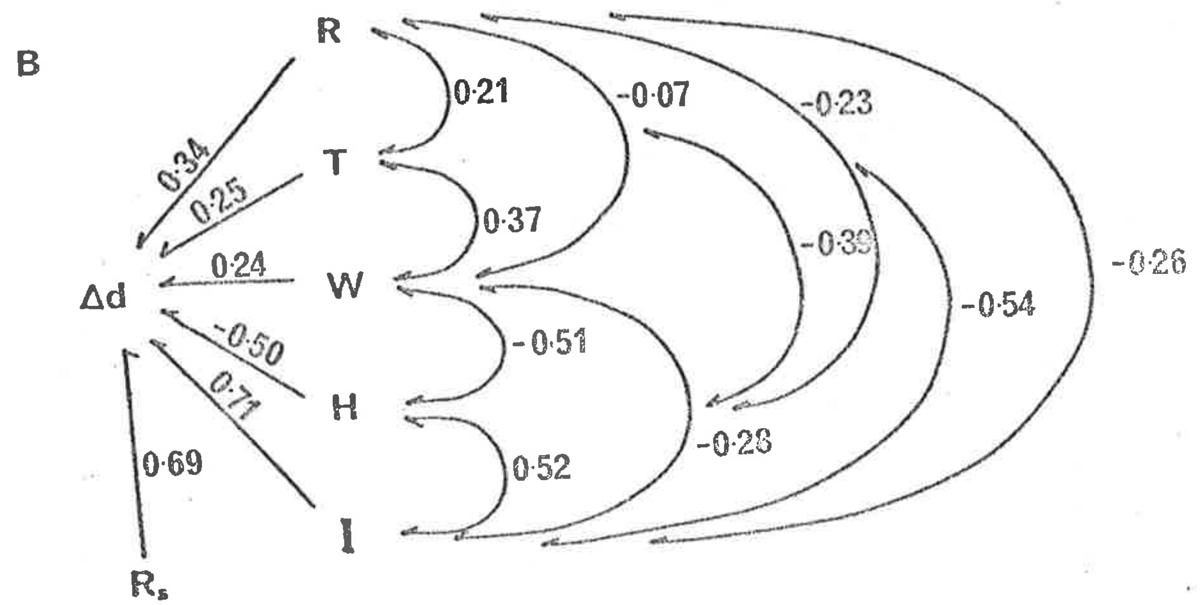


Fig. 6.11. Path diagram of the effect of meteorological factors and initial soil water content on drying rate from tilled (A) and non-tilled (B) plots (1979 exp.).

Table 6.10. Path coefficient of observed variables upon drying rate from tilled and non-tilled plot (1979).

Plot	Via	Drying versus				
		R	T	W	H	I
Tilled plot	R	0.57[1]	0.12	-0.04	-0.13	-0.27
	T	0.06	0.29	0.01	-0.08	-0.14
	W	-0.04	0.20	0.55	-0.28	-0.13
	H	0.06	0.06	0.11	-0.21	-0.09
	I	-0.29	-0.31	-0.14	0.32	0.62
	r_{iy}	0.36	0.36	0.49	-0.38	0.31
Non-tilled	R	0.34	0.06	-0.02	-0.08	-0.09
	T	0.05	0.25	0.09	-0.10	-0.14
	W	-0.02	-0.09	0.24	-0.12	-0.07
	H	0.12	0.20	0.26	-0.50	-0.26
	I	-0.18	-0.21	-0.20	0.37	0.71
	r_{iy}	0.31	0.21	0.37	-0.43	0.15

[1] direct effect.

In the Spring, temperature and radiant energy were the meteorological factors controlling drying. In the Winter, the role of these factors was replaced by wind speed. Relative humidity influenced drying if the soil water content was high enough (1978 experiment 1). However, as soon as the soil water content decreased (1978 experiment 2, and 1979) the influence of relative humidity became less important.

6.2 Tilth mellowing

6.2.1 Introduction

It has been shown (section 5.1) that the tensile strength of synthetic aggregates decreases with wetting and drying. If this occurs also in the field, it could be very useful to use the natural wetting and drying to reduce soil strength as a soil management practice.

Usually a single pass of a tillage implement is not sufficient to form a good seed bed from a settled soil. Natural wetting and drying, therefore, can be used by allowing the soil, after the first implement pass, to dry during the day and to wet during the night for several days before doing the second implement pass. Since tillage increases the intensity of wetting and drying (section 6.1), it can be expected that this will result in a decrease in the strength of the clods, and hence, these clods will be more easily broken by mechanical impact of the tillage implement in the second implement pass. The decrease in clod strength due to natural wetting and drying is referred to as "tilth mellowing".

It seems that these natural processes have been used by some farmers in seed bed preparation practice. According to Jones, Hamblin and Leonard (1941) the Houston clay soil of the U.S.A. is very difficult to handle in most seed bed preparation practices. When this soil is ploughed, it turns up in large clods, and only nature, by wetting and drying, can reduce the strength of these clods without excessive cost. Woodburn (1944) noticed that some farmers in the Black prairie section of Mississippi and Alabama plough their land as long as possible before planting. By doing this, they expect that there will be enough time for weather to break up and to reduce the strength of the clods.

The dependence of a farmer on weathering action to reduce clod strength to a value where breakage is possible has also been noted by Fountaine *et al.* (1956). Baver *et al.* (1972) observed that some farmers allowed their land to dry out thoroughly and then be rewetted slowly. When it has become dry again, this soil is more easily tilled and can produce a good seed bed.

Although these processes seem to have a great practical importance, there is still limited quantitative data. Lyles and Woodruff (1961) are probably the only workers to have shown the change, both in the decrease in the size distribution and in the mechanical stability of clods due to weathering action. However, they did not interpret their data in terms of tilth mellowing. This was probably because the aim of their experiment was to study the resistance of soil to wind erosion.

Arndt (1964) conducted a comprehensive experiment to study some physical problem of the lateritic red earths around Katherine in Northern Australia. By using the term "physical conditioning" to describe the action of natural wetting and drying in modifying the physical properties of a soil, he suggested that during the physical conditioning process large clods are reduced by slaking and cultivation, and at the same time, the dusty fraction is partly aggregated by wetting and intense sun drying.

The aim of the experiments described here was to study the effect of the natural wetting and drying in tilled soil (which is more intensive than in non-tilled soil as discussed in section 6.1) on the strength of the clods produced by tillage. If there is a decrease in clod strength, then allowing this soil to wet and dry naturally for several days after the first implement pass will result in an increase in the proportion of smaller aggregates produced by a second implement pass. If this is the case, then it will be a good idea to delay the second implement pass for a few days, so that the soil can be tilled to produce a good seed bed with minimum energy consumption and cost.

6.2.2 Materials and Methods

Tillage

The experiments were conducted in the Spring (September-October) 1978 on Urrbrae fine sandy loam, and were repeated in the Winter (June) 1979). To obtain data from a different soil, the third experiment was conducted at the Charlick experiment Station of the Waite Institute at Strathalbyn. Some properties of these soils have been described in section 3.1.

At the Urrbrae site, the soil had been bare for several years and tillage was done with a tyne cultivator to a depth of about 10 cm. At Strathalbyn, where the soil had carried pasture for a number of years, the first implement pass was done with a chisel plough, and the second pass was with a tyne cultivator. As with the Urrbrae experiment, tillage was done to a depth of about 10 cm.

Wetting and drying

The wetting and drying used was the natural wetting and drying. This was done by allowing the soil (after the first implement pass) to dry during the day as a result of solar radiation, wind, etc., and to wet during the night by capillary action from the layer below, condensation of water vapour within the tilled layer and from the atmosphere, etc. The wetting and drying was calculated from the daily changes in soil water content. Soil water content was determined at 9.00 a.m. and at 5.00 p.m. each day. The total wetting and drying was given by the cumulative differences between these successive soil water contents. The measurement of soil water content and the calculation of the amount of wetting and drying was done as described in section 6.1.

Because of transport limitations, the measurement of soil water content was done only at the Urrbrae experiment. At Strathalbyn, the changes in soil properties was measured as a function of time (in days) after the first implement pass.

Measurement of clod strength

The strength of the clods was determined by the "drop shatter" test as used in determining the strength of coals (ASTM, 1946). This method has been used successfully to determine clod strength by Marshall and Quirk (1950), Gill and McCreery (1960) and Ingles (1963). To do this, 6 clods (each time) of about 100 mm diameter which had been subjected to different amounts of wetting and drying were collected from the tilled plots. To obtain different amounts of natural wetting and drying, clods were collected and measured at different numbers of days after tillage. To eliminate any effects resulting from differences in water status of the clods, the test was done after the clods had been equilibrated to the same water matric potential. The clods were wetted by capillary action to near saturation, and then dried to a water matric potential of -100 kPa in a pressure plate apparatus for 2 days. The drop shatter test was done by dropping the clods individually from a height of 200 cm, and then measuring the resulting clod size distribution by dry sieving.

To obtain a relationship between the amount of energy required to break the clods and the size distribution of the resulting clods/aggregates, for the 1979 Urrbrae experiment, the drop was done from several different heights, i.e., 60, 120, 180, and 240 cm. The energy (J) required was calculated by multiplying the clod mass (kg), the height of the drop (m), and the acceleration of gravity (9.81 ms^{-2}).

The change in the strength of the clods was also evaluated by measuring the size distribution of the clods produced by the second implement pass. This was based on the assumption that due to the formation of internal cracks caused by unequal swelling and shrinkage resulted from wetting and drying, the clods (produced by the first implement pass) become weaker, and hence, would be more easily broken by the tillage implement. With this phenomenon, there should be a greater amount of the smaller fraction produced by the second implement pass with increasing time, and hence wetting and drying, after the first tillage. One (for the 1978 experiment) and 3 (for the 1979 experiment) samples of each 7 - 10 kg soil were collected immediately after the second implement pass. To avoid the influence of tractor wheels, the samples were collected from between the tractor wheel tracks to a depth of about 10 cm.

Moulds of 40 X 20 X 10 cm were pressed into the tilled plots down to the depth of tillage, and the samples were gently collected with a spade into a plastic basket. Clod sorting was done by dry sieving into the following size ranges: > 40 mm (measured individually with a rule; 9.5 - 40, 6.7 - 9.5, 4.0 - 6.7, 2.0 - 4.0, 1.0 - 2.0, and < 1.0 mm. The weight of each group was expressed as a percentage of the total weight of the sample.

6.2.3 Results and Discussion

Clod strength

There was a tendency for the wetting and drying to decrease the strength of the clods produced by tillage. As the clods were subjected by wetting and drying they became more easily broken in the drop shatter test. This was shown by the increase in the proportion of the smaller fraction, and at the same time a decrease in the proportion of the larger fraction, resulting from the drop shatter test (Table 6.11).

Table 6.11. Effect of cumulative wetting and drying ($\Sigma \Delta W$) on clod strength of Urrbrae soil, as shown by the size distribution of the clods produced by the drop shatter test.

$\Sigma \Delta W$	% clods with diameters of (mm)					
(%)	> 9.5	6.7-9.5	4.0-6.7	2.0-4.0	1.0-2.0	< 1.0
0	64.2	6.2	8.0	6.4	7.4	5.4
20.3	54.0	10.2	8.3	9.5	8.0	9.0
43.9	42.0	8.1	9.4	14.6	12.4	12.0
78.1	36.5	11.6	12.4	14.8	12.0	11.6
118.4	31.1	8.9	11.9	13.9	15.7	13.6
161.7	30.4	10.6	12.2	13.0	15.0	14.2

A plot of the cumulative of wetting and drying against the proportion of the aggregate fraction smaller than 4.0 mm diameter yielded an asymptotic curve. Within an experimental error, this curve can be expressed by the exponential euqation

$$P_{\delta(\Sigma \Delta W)} = A + a \left[1 - \exp(-a'\Sigma \Delta W) \right] \qquad (6.13)$$

where $P_{\delta(\Sigma \Delta W)}$ is the proportion of the clods smaller or larger than diameter, δ (in this case smaller than 4.0 mm diameter), after a cumulative wetting and drying of $\Sigma \Delta W$, and A, a, and a' are adjustable parameters. In fact A is the proportion of clods larger or smaller than diameter, δ, of the clods that had not been subjected to wetting and drying ($\Sigma \Delta W = 0$).

The resulting equation was (Figure 6.12)

$$P_{<4.0}(\Sigma \Delta W) = \underset{(\pm 2.62)}{18.54} + \underset{(\pm 3.20)}{24.65} [1 - \exp(-\underset{(\pm 0.009)}{0.027} \Sigma \Delta W)] \quad (6.14)$$

To study the amount of energy required to break up the clods, the logarithm input energy was plotted against the mean weight diameter (MWD) of the resulting clods (Urrbrae 1979). The mean weight diameter was calculated by the method of Youker and McGuinness (1957), and the resulting equation was a straight line

$$MWD = C - c \log_{10} E. \quad (6.15)$$

Here, MWD is the mean weight diameter (mm), E is the input energy (J), and C and c are adjustable parameters.

The resulting parameters C and c (Table 6.12) decrease with increasing amounts of wetting and drying. This shows that wetting and drying decrease the amount of the input energy required to break the clods to produce a given value of mean weight diameter. For instance (Figure 6.13), to produce clod size distribution with the MWD of 15 mm, an input energy of 1.78 J was required for the clods which had not been subjected to wetting and drying, whereas only 0.56 J was required for the clods which had been subjected to a wetting and drying of $\Sigma \Delta W$ = 26.8% since the first implement pass.

The decrease in the strength of clods with wetting and drying can be explained in terms of crack formation. As discussed in section 5.1, wetting and drying a soil causes swelling and shrinkage. Since swelling and shrinkage is not equal throughout the mass of the soil, it may produce cracks which decrease the strength of the soil. It is important to

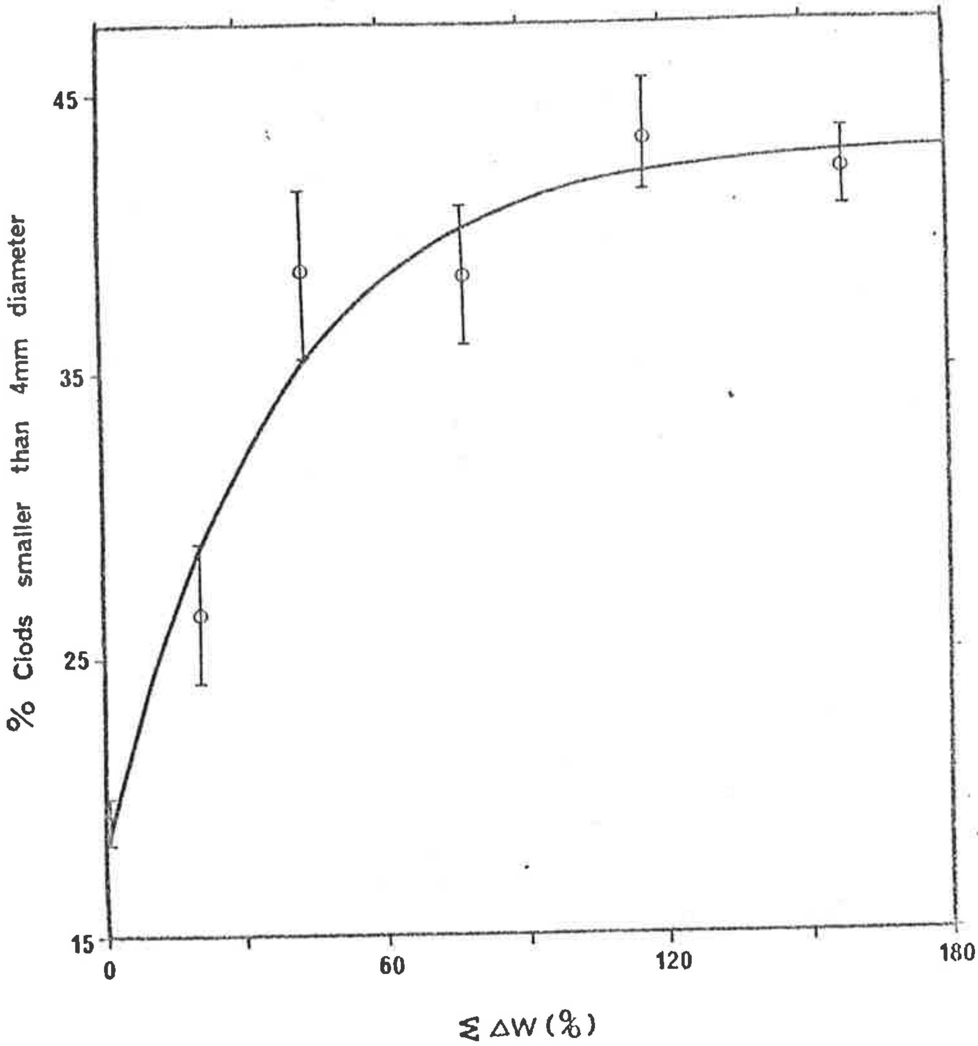


Fig. 6.12. Effect of wetting and drying (Σ Δ W) on clod strength (as shown by the proportion of fraction smaller than 4.0 mm diameter resulting from the drop shatter test) for Urrbrae soil.

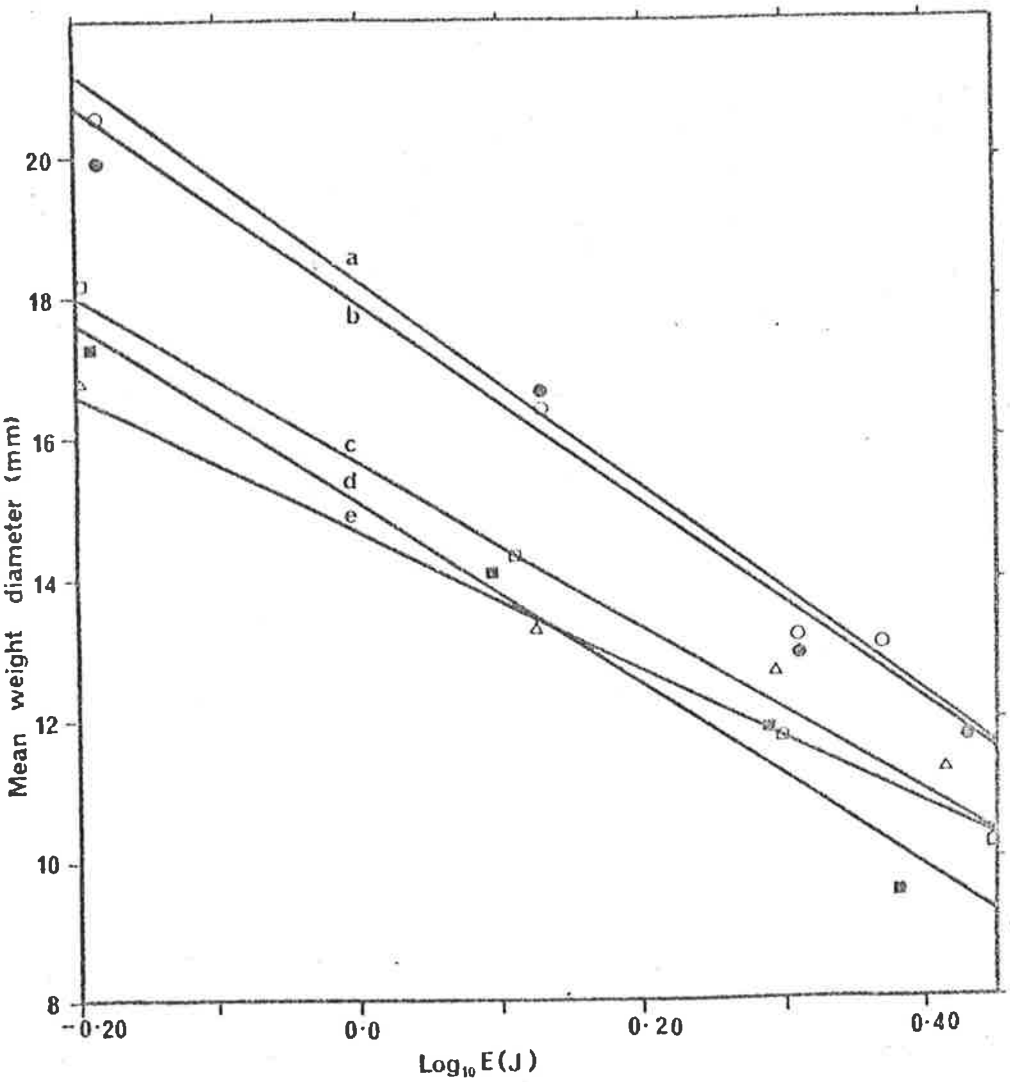


Fig. 6.13. Effect of wetting and drying ($\Sigma \Delta W$) on the relationship between $\log_{10}E$ and the MWD of aggregates resulting from the drop shatter test on Urrbrae soil.
a. $\Sigma \Delta W = 0$; b. $\Sigma \Delta W = 21.7\%$;
c. $\Sigma \Delta W = 26.8\%$; d. $\Sigma \Delta W = 35.4\%$;
e. $\Sigma \Delta W = 43.3\%$.

Table 6.12. Values of C and c parameters and coefficient of determination (r^2) of equation (6.15) as influenced by wetting and drying ($\Sigma \Delta W$).

$\Sigma \Delta W$ (%)	C	c	r^2
0	18.15	14.40	0.98
21.7	17.86	14.09	0.97
26.8	15.67	11.67	0.98
35.9	15.12	13.06	0.97
43.3	14.76	9.76	0.93
60.8	15.00	11.99	0.94

realize that this experiment was not aimed to discuss the gross swelling and shrinkage of normally-swelling clays. It is believed that even minute soil "residual shrinkages" are sufficient for crack initiation and propagation. It has been shown in the laboratory study (section 5.1) that wetting and drying between matric water potentials of -10 kPa and -100 kPa (corresponding to gravimetric soil water contents of about 21% and 18%) were able to decrease the tensile strength of artificial aggregates. The development of cracks in a clod with wetting and drying is shown in plate 6.1. The occurrence of cracks accompanying shrinkage on drying of a clod has also been noticed by Wilton (1963).

Larson and Allmaras (1971) have pointed out that as water is lost from a soil, the specific volume may change, but the mass of the solid remains constant. Since there is a decrease in specific volume creating horizontally oriented tensile stress, shrinkage cracks may form along vertical planes (or, more generally, along planes normal to the drying surface) where the soil may be wetter and has a lower tensile strength.

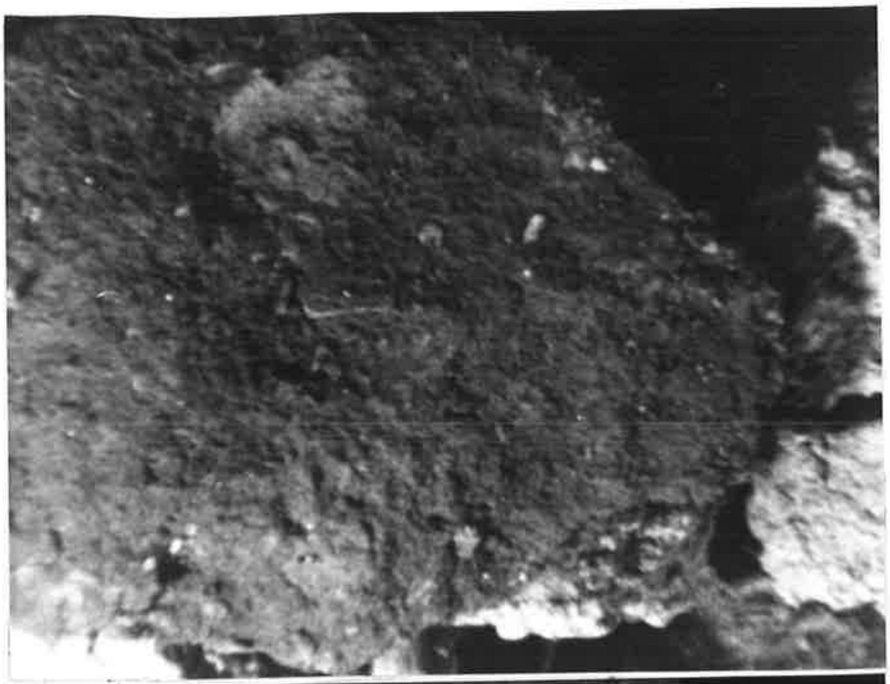
Plate 6.1. The development of cracks in a clod of Urrbrae loam in the field observed by time-lapse photography:

a. Initial stage of crack formation.

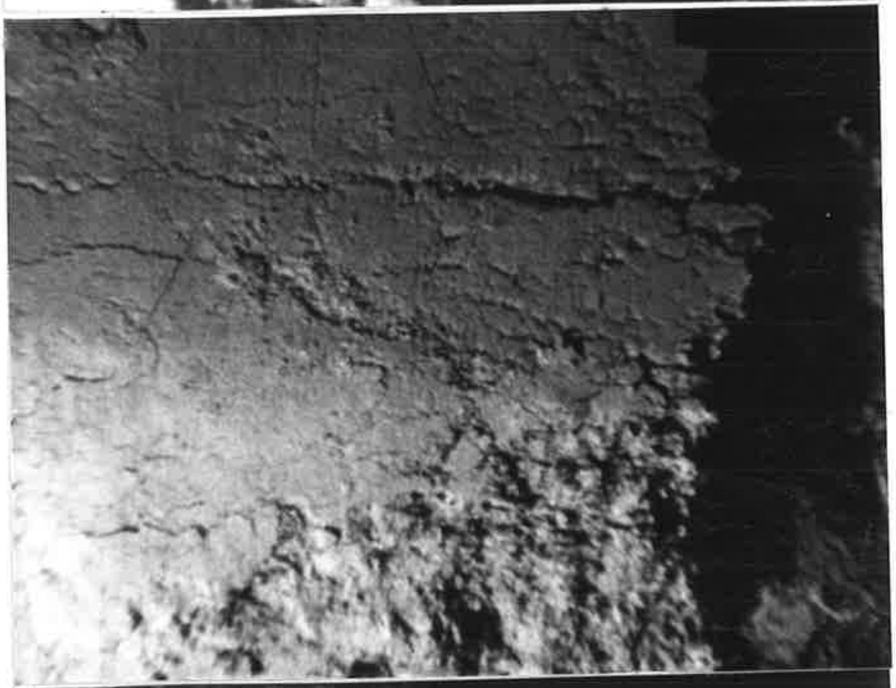
b. Cracks have already been formed.

c. Some cracks closed after wetting.

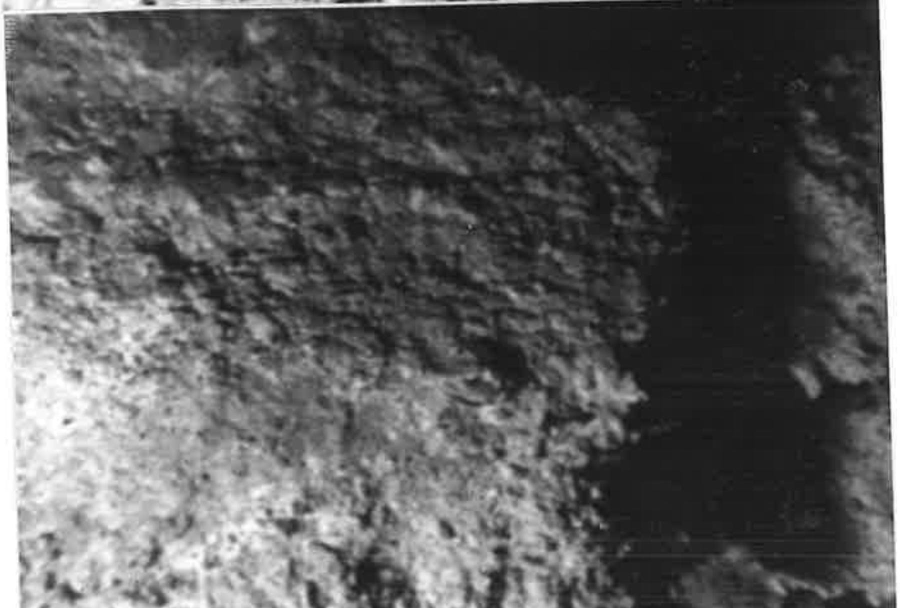
a



b



c



According to Russell (1973) allowing a clod to dry and wet not only causes some slaking of crumbs from its outer surface, but also causes some slaking to develop internally due to uneven shrinking of the clod during drying, and perhaps to some extent by compression of entrapped air during wetting.

A decrease in mechanical stability of clods due to weathering action has also been found by Lyles and Woodruff (1961). They investigated the relationship between soil density (expressed as a percentage of maximum density) and the proportion of clods larger than 6.4 mm diameter. They found that the resistance of clods to weathering action was positively correlated with the density. Further, they showed that the decrease in the mechanical stability of clods was very marked on silty clay loam and sandy loam, but was less significant in clay soils.

Clod size distribution

As expected, the change in clod strength was followed by the change in the size distribution of the clods produced by the second implement pass. Thus, with decreasing clod strength (due to wetting and drying), the clods were more easily shattered by the mechanical impact of the tillage implement. As a result, the proportion of the smaller aggregate fraction increased, and at the same time, the proportion of the larger fraction decreased (Figure 6.14). The change in the size distribution was very rapid at first (mainly in the first 3-5 days after the first implement pass) and then gradually slowed down with further wetting and drying or time. These data were well described by equation (6.13), and the resulting values of the parameters A, a, and a' for the clods with the diameter of > 9.5 mm; < 6.7 mm; and < 4.0 mm are given in Table 6.13, and the resulting graphs in Figure 6.15.

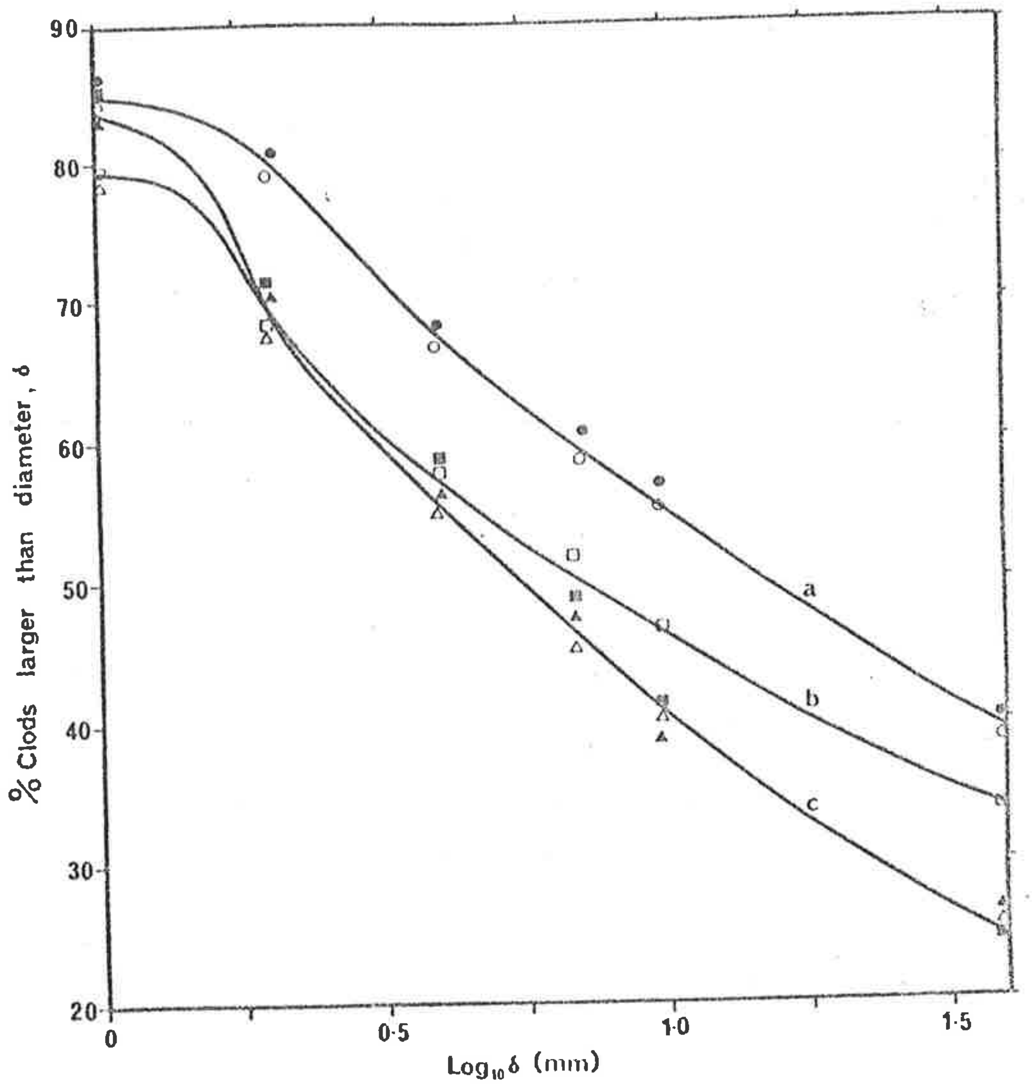


Fig. 6.14. Effect of wetting and drying (Σ Δ W) on the size distribution of clods produced by the second implement pass (Urrbrae - 1978).
a. Σ Δ W = 0 (○) and Σ Δ W = 0.4% (●);
b. Σ Δ W = 7.9% (□); c. Σ Δ W = 28.5% (■):
Σ Δ W = 43.9% and Σ Δ W = 81.5% (△), (▲).

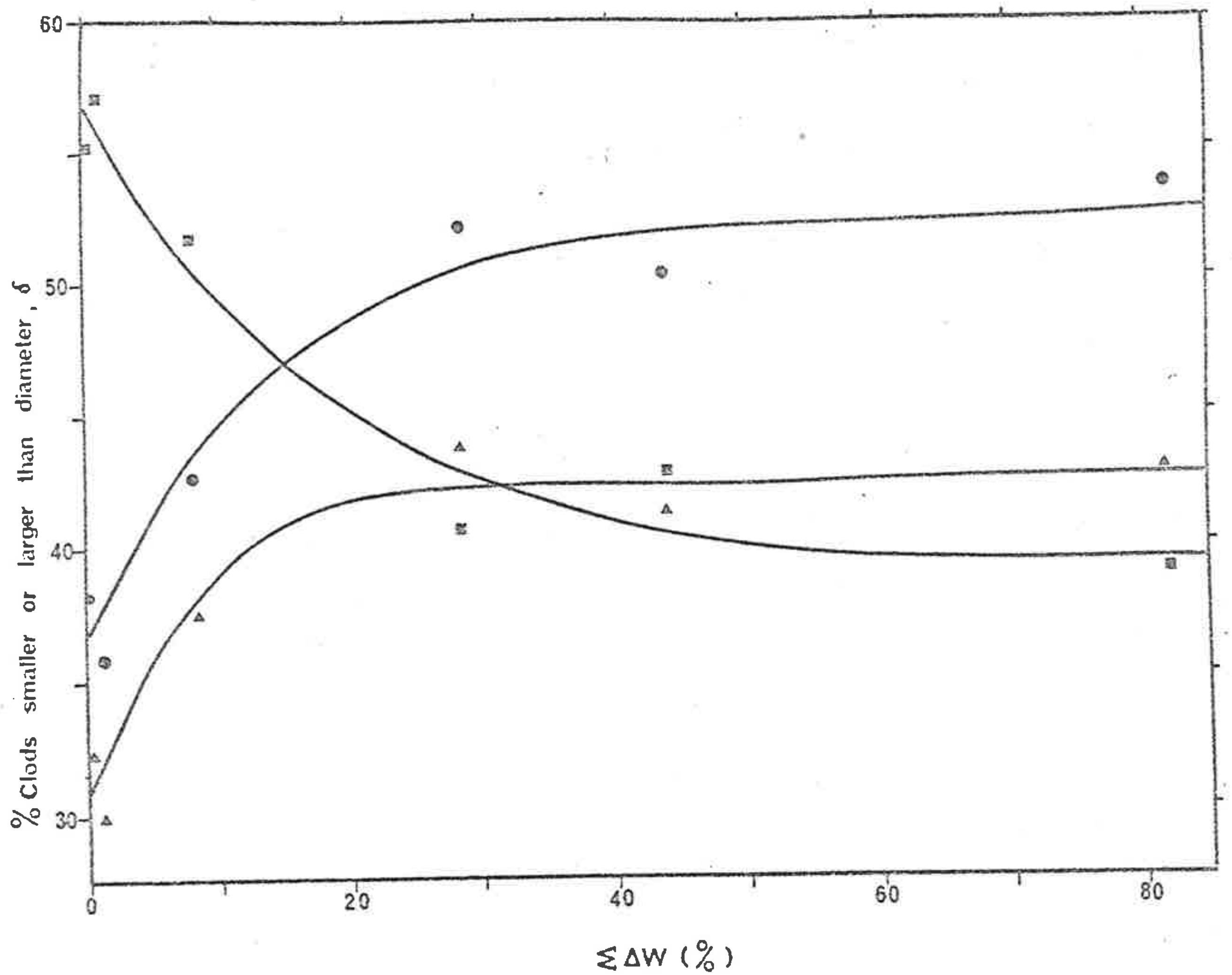


Fig. 6.15. Effect of wetting and drying (Σ Δ W) on the proportion of clods smaller or larger than diameter, δ, produced by the second implement pass (Urrbrae, 1978). The curves are fit of equation (6.13), and the measurements are given by: (▲) < 4.0 mm; (●) < 6.7 mm; and (■) > 9.5 mm diameter.

Table 6.13. The values of the parameters A, a, and a' of equation (6.13) for the Urrbrae 1978 experiment.

Clod diameter (mm)	A	a	a'
> 9.5	56.40 (±1.38)	-17.24 (±2.25)	0.054 (±0.021)
< 6.7	36.78 (±1.51)	15.99 (±2.18)	0.067 (±0.030)
< 4.0	30.79 (±1.33)	11.67 (±1.69)	0.124 (±0.060)

It was surprising that with a small soil water content fluctuation (Figure 6.1), there was a large increase in the proportion of smaller fraction when the second implement pass was done on day 3. This supports the previous suggestion that minute residual shrinkages are able to initiate and propagate cracks in the clods produced by tillage. In addition, it is likely that besides the decrease in clod strength (due to wetting and drying), this increase was also caused by the direct effects of wetting and drying. Thus wetting and drying themselves were able to disintegrate the clods produced by tillage. This will be discussed further later in this section.

The result of the 1979 Urrbrae experiment was in good agreement with the previous experiment. A slight difference was that the major change in clod size distribution did not occur in the first few days, but after the soil had been subjected to a larger amount of wetting and drying (Figure 6.16).

It is necessary to note that in the first few days after the first implement pass there were cloudy and rainy days. It is, therefore, assumed that the clods did not dry sufficiently for cracks to develop.

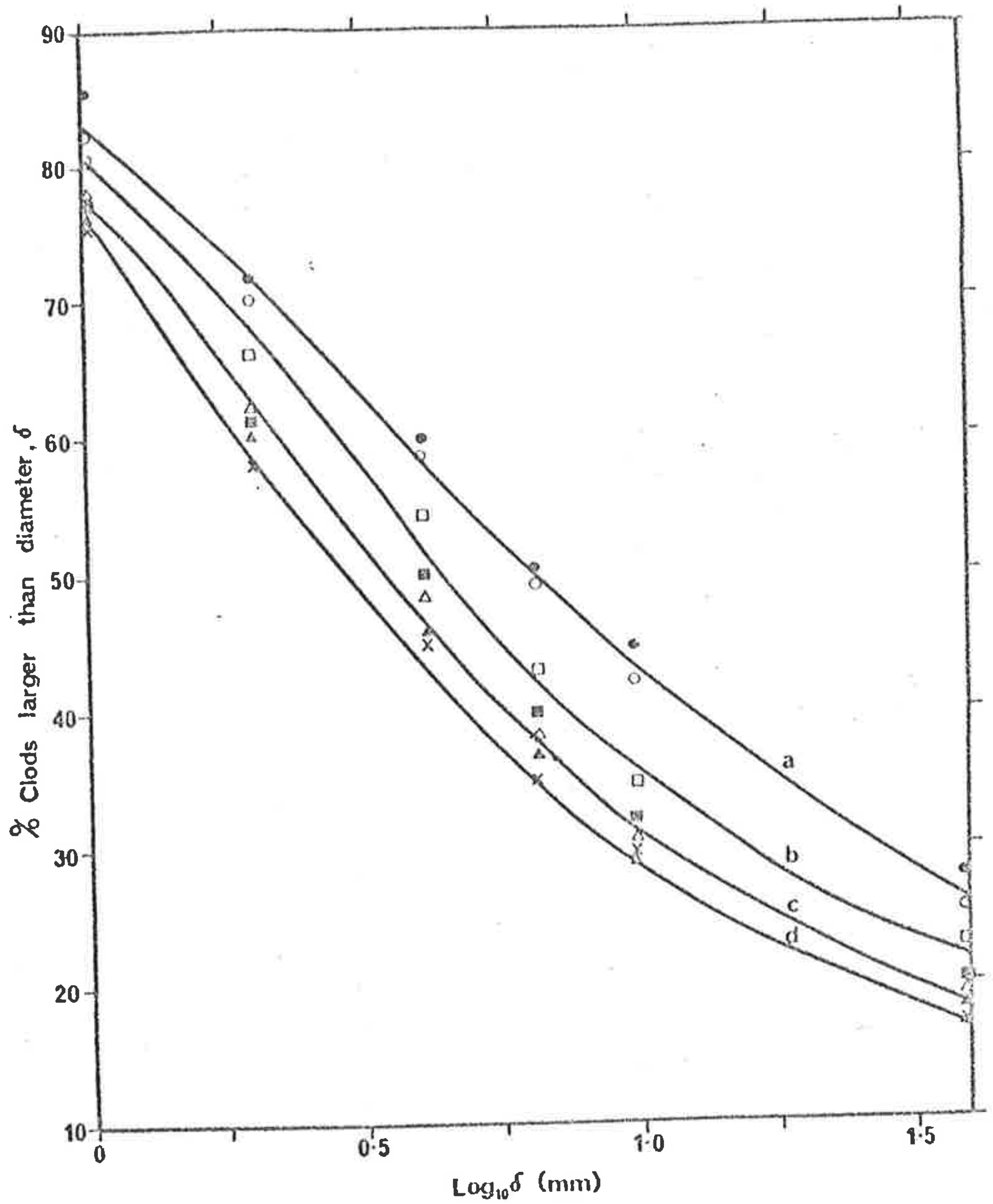


Fig. 6.16. Effect of wetting and drying ($\Sigma \Delta W$) on the size distribution of clods produced by the second implement pass (Urrbrae - 1979).
a. $\Sigma \Delta W = 0$ (○) and $\Sigma \Delta W = 4.6\%$ (●),
b. $\Sigma \Delta W = 21.7\%$ (□); c. $\Sigma \Delta W = 26.8\%$ (■) and $\Sigma \Delta W = 40.47\%$ (△); d. $\Sigma \Delta W = 60.8\%$ (▲) and $\Sigma \Delta W = 76.1\%$ (×).

The cumulative water content change was high enough ($\Sigma \Delta W$ = 21.7% on day 5, compared to $\Sigma \Delta W$ = 7.9% on day 3 in the 1978 experiment when the third treatment was done), however, this mostly originated from wetting which is less likely to initiate crack formation. As a consequence, the strength of the clods did not much change and there was therefore little change in the size distribution of the clods produced by the second implement pass. This suggestion can be supported by the result shown in Figure 6.13 which shows that there was no difference in the relationship between the log input energy and the mean weight diameter of the clods resulting from the drop shatter test of the clods which had not been subjected to wetting and drying ($\Sigma \Delta W$ = 0%) and that of the clods which had been subjected to a wetting and drying of $\Sigma \Delta W$ = 21.7%. This indicates that with the same amount of input energy, the clods produced by the second implement pass done at $\Sigma \Delta W$ = 0% will have the same mean weight diameter as when the second implement pass was done at $\Sigma \Delta W$ = 21.7% in this case.

Another factor which might also have influenced this difference was the soil water content at the time of tillage (see Figures 6.1 and 6.2). The importance of soil water content in determining the size distribution of clods produced by tillage has been discussed extensively in section 2.1.4. For the Urrbrae red brown earth, Ojeniyi and Dexter (1979a) found that tillage at 17% soil water content produced the smallest proportion of large clods using a similar implement to that used here. Further, they showed that tillage at 15.8% soil water content produced about 57% of clods larger than 4.0 mm diameter, whereas tillage at 18.3% soil water content produced 66% of clods larger than 4.0 mm diameter.

The soil water contents at the times of tillage for the first, second, third and fourth treatments in the 1978 experiment were 15.0%

(when the second implement pass was done at day 0 immediately after the first implement pass, or $\Sigma \Delta W$ = 0%), 15.1% (day 1, $\Sigma \Delta W$ = 0.4%), 14.6% (day 3, $\Sigma \Delta W$ = 7.9%), and 19.2% (day 8, $\Sigma \Delta W$ = 28.5%). In the 1979 experiment, the soil water contents were 15.9% (day 0), 14.0% (day 1, $\Sigma \Delta W$ = 4.6%), 18.6% (day 5, $\Sigma \Delta W$ = 21.7%), and 20.9% (day 8, $\Sigma \Delta W$ = 26.8%).

From the result of the 1978 experiment, it was expected that the major change in the size distribution of the clods produced by the second implement pass would occur on the 3rd or 4th day after the first implement pass. Unfortunately, the soil water content on these days was too high to do tillage (19.5% on the day 3, and 19.6% on the day 4). Even when tillage was done on day 5, the soil water content was still too high (18.6%), as it was done on day 8 (20.4%).

The data were fitted to equation 6.13, and the resulting values of the parameters A, a, and a' are given in Table 6.14. The curves of these equations are shown in Figure 6.17.

Table 6.14. The values of the parameters A, a, and a' of equation (6.13) (Urrbrae, 1979).

Clod diameter (mm)	A	a	a'
> 9.5	43.97 (±1.18)	-15.08 (±1.94)	0.038 (±0.013)
< 6.7	49.10 (±1.10)	13.79 (±1.78)	0.037 (±0.013)
< 4.0	40.85 (±0.92)	13.69 (±2.07)	0.029 (±0.010)

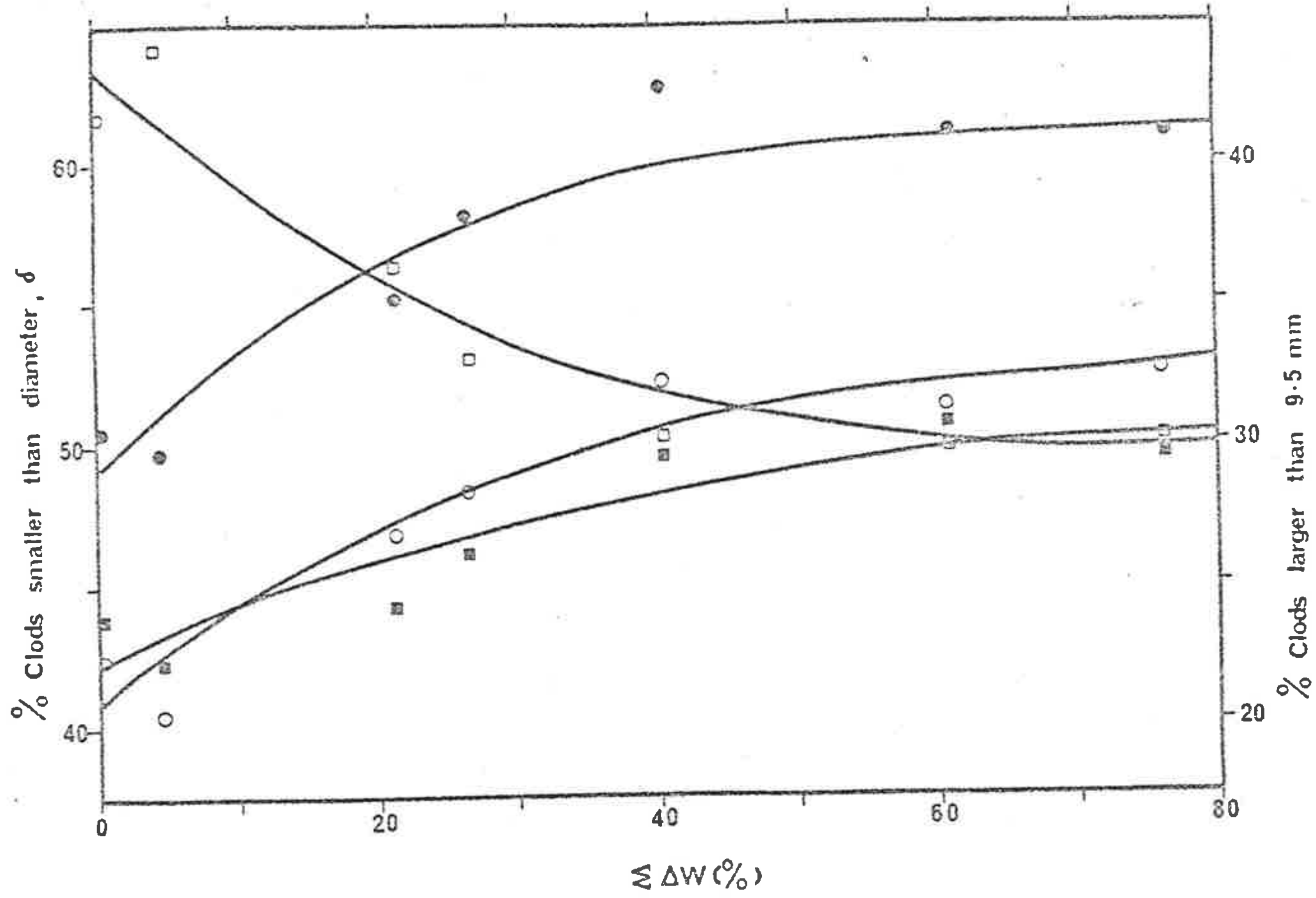


Fig. 6.17. Effect of wetting and drying (Σ Δ W) on the proportion of clods larger or smaller than diameter, δ, produced by the second implement pass (Urrbrae, 1979). The curves are fit of equation (6.13), and the measurements are given by: (◉) < 6.7 mm; (○) < 4.0 mm; and (□) > 9.5 mm. The contribution of wetting and drying alone in increasing clods < 6.7 mm is given by (●).

As in the laboratory study (section 5.1), the decrease in clod strength due to wetting and drying occurred also in the Strathalbyn experiment. Thus delaying the second implement pass a few days after the first implement pass increased the proportion of the smaller fraction. The result was very similar to the result of the Urrbrae 1978 experiment where the major change in the size distribution of the clods produced by the second implement pass occurred a few days after the first implement pass (Figure 6.18). The soil water contents at tillage for the first, second, third, and fourth treatment were 13.7% (day 0), 13.6% (day 1), 13.9% (day 2), and 14.4% (day 4).

Since the changes in soil water content were not measured, the data could not be fitted to equation (6.13) directly. To overcome this problem, equation (6.13) was modified to

$$P_{\delta(t)} = A + a \; [1 - \exp(-a''t)] \qquad (6.16)$$

where t is the time (days) after the first implement pass.

The resulting values of A, a, and a" parameters is given in Table 6.15, and the curves for this equation are shown in Figure 6.19.

Table 6.15. The values of the parameter A, a, and a" of equation (6.16) for the Strathalbyn experiment

Clod diameter (mm)	A	a	a"
> 9.5	69.69 (±1.63)	-12.69 (±1.85)	0.461 (±0.166)
< 6.7	24.43 (±1.45)	10.45 (±1.63)	0.497 (±0.189)
< 4.0	18.31 (±1.15)	7.56 (±1.30)	0.452 (±0.193)

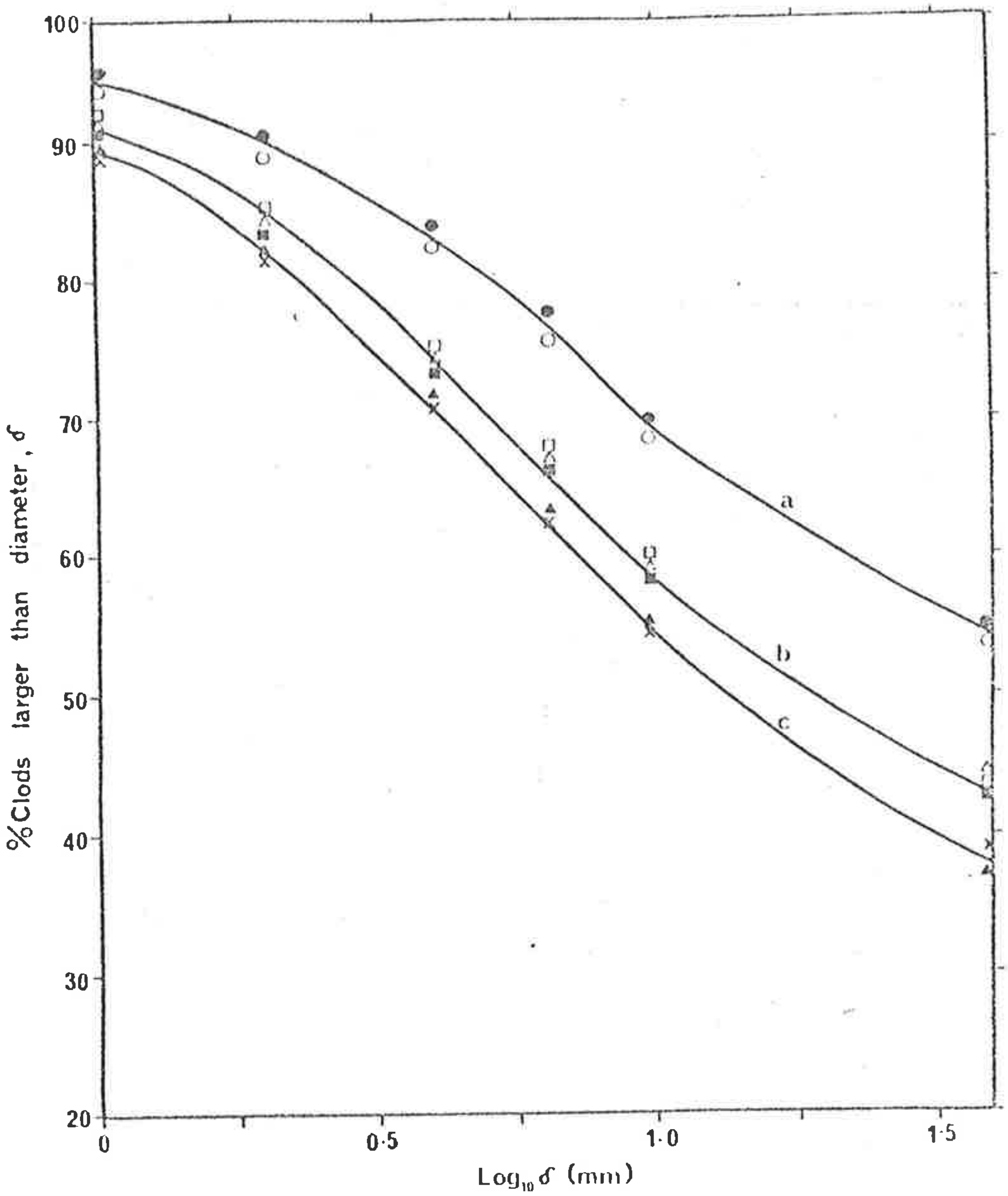


Fig. 6.18. Effect of wetting and drying (as shown by time after tillage) on the size distribution of clods produced by the second implement pass (Strathalbyn). a. day 0 (○) and day 1 (●); b. day 2 (□), day 4 (■) and day 8 (△); c. day 10 (▲) and day 16 (×).

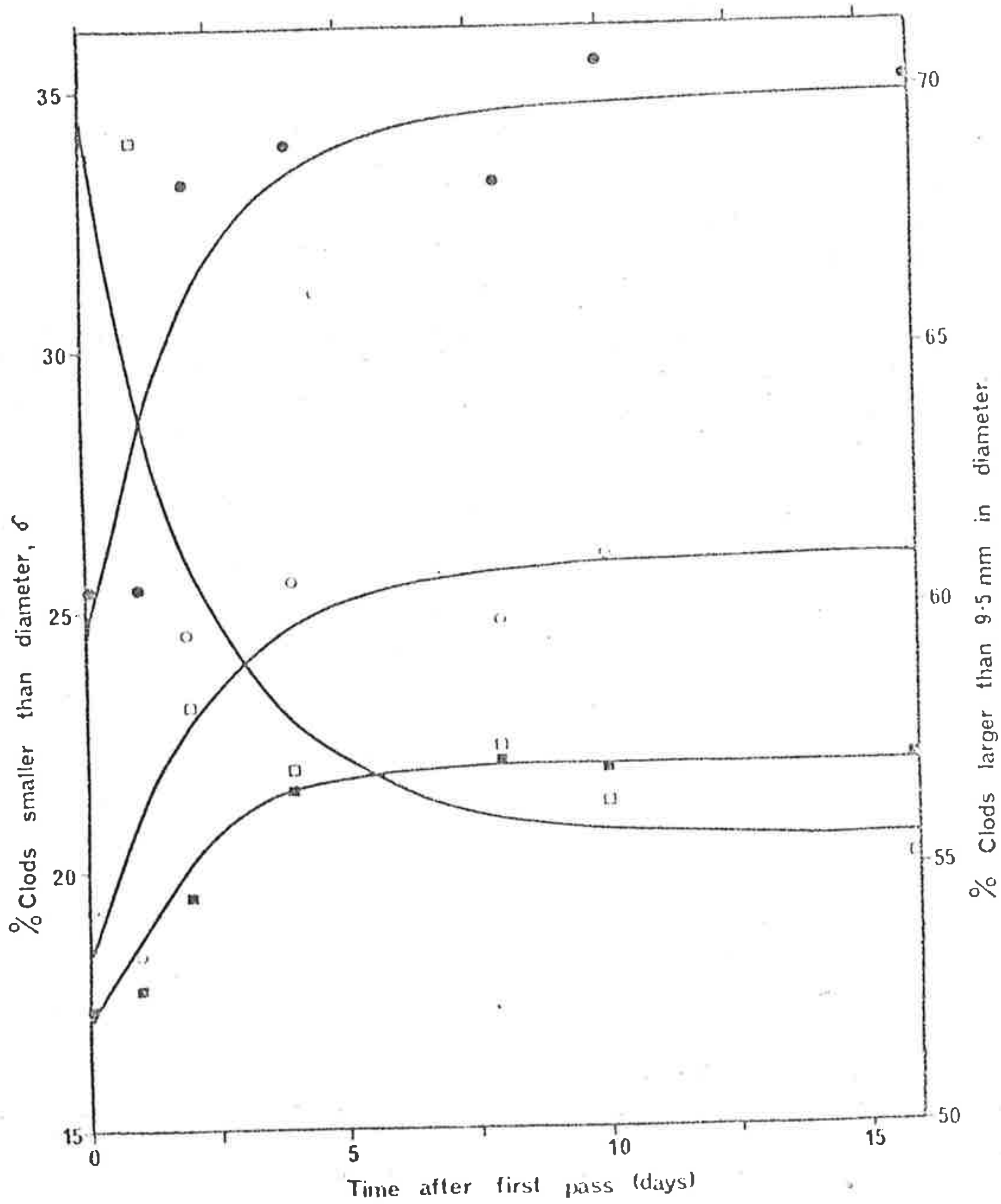


Fig. 6.19. Effect of wetting and drying (as shown by time after tillage) on the proportion of clods smaller or larger than diameter, δ, produced by the second implement pass (Strathalbyn).
The curves are fit of equation (6.16), and the measurements are given by (●) < 6.7 mm; and (O) < 4.0 mm; (□) > 9.5 mm. The contribution of wetting and drying alone in increasing clods < 6.7 mm diameter is given by (■).

It is interesting to note that there was a tendency for an increase in the strength of the clods one day after the first implement pass. This was shown by the decrease in the proportion of the smaller fraction when the second pass was done on this day. It is suggested that a small loss of water from a soil is not able to initiate crack formation, and may even cause soil particles to move closer together. Since the attractive forces increase with decreasing distance between particles, this process will result in an increase in soil strength. Wilton (1963) has found that at first, drying a clod results in an increase in the shear strength, the clod becoming tougher and hence more difficult to break. An increase in the shear cohesion (C) and internal friction angle (Ø) due to slow drying has also been found by Camp and Gill (1969).

It has been suggested that besides the decrease in clod strength, the increase in the proportion of the smaller fraction found after the second implement pass was caused by the direct actions of wetting and drying themselves. It seems that stresses and strains which develop during wetting and drying, and to some extent the action of entrapped air (when there is a rapid wetting caused, for example, by rainfall) are sometimes able to disintegrate clods into smaller fragments. This mechanism has been proposed by Russell (1973) and is supported by the results of this experiment (Table 6.16).

<u>Table 6.16.</u> Effect of natural wetting and drying (as shown by $\Sigma \Delta W$ after tillage) on clod size distribution in a tilled soil (Urrbrae - 1978).

$\Sigma \Delta W$	% clods with diameter (mm)					
(%)	> 9.5	6.7-9.5	4.0-6.7	2.0-4.0	1.0-2.0	< 1.0
0	54.2	6.3	6.4	9.3	8.5	9.3
43.9	53.8	5.6	7.7	9.6	8.9	15.4
109.7	41.8	8.6	10.2	12.8	12.3	15.0

Arndt (1964) found that slaking of clods caused by rainfall is one of the important factors in modifying the structure in a tilled soil. By using the term "surface roughness", R, that is

$$R = \left(\frac{\text{actual length - direct length}}{\text{direct length}} \right) \times 100 \qquad (6.17)$$

he showed that tilled soil which had a roughness of R = 21.6 (before rain) decreased to R = 1.6 (after rain). The decrease in random roughness of several tillage treatments on various soil types has also been measured by Allmaras *et al.* (1977) and by Dexter (1977).

Fox (1964) has suggested that due to non-uniformity of wetting and drying throughout the soil mass, the associated swelling and shrinking create regions of failure during drying. Further, he demonstrated that clods with diameters of 12 - 40 mm were prevalent when the bulk field sample was moist, but as these large clods dried to a matric water potential of about -3.2 MPa, they spontaneously broke into aggregates rather uniformly with diameters of 2.0 - 4.0 mm.

As a consequence of the result of the 1978 experiment (Table 6.16), it was decided to study the contribution of wetting and drying alone in modifying the size distribution of the clods in a tilled soil. This was done in the 1979, in both the Urrbrae and the Strathalbyn experiments by measuring clod size distribution prior to the second implement pass (3 samples of 7 kg for each measurement). The results were fitted to equation (6.14) for the Urrbrae experiment, and to the equation (6.17) for the Strathalbyn experiment. The resulting equations were

$$P_{<6.7(\Sigma\ \Delta\ W)} = \underset{(\pm 0.99)}{41.93} + \underset{(\pm 3.14)}{10.71}\ [1 - \exp(\underset{(\pm 0.015)}{-0.023}\ \Sigma\ \Delta\ W)] \qquad (6.18)$$

for the Urrbrae experiment, and

$$P_{<6.7(t)} = \underset{(\pm 0.81)}{16.94} + \underset{(\pm 0.91)}{5.15}\ [1 - \exp(\underset{(\pm 0.218)}{-0.514}\ t)] \qquad (6.19)$$

for the Strathalbyn experiment.

It can be seen (Figures 6.17 and 6.19) that wetting and drying alone contribute about 40% of the total increase in the fraction smaller than 6.7 mm diameter observed after a second implement pass.

6.3 Tensile Strength and Aggregate Water Stability

6.3.1 Introduction

It has been shown in section 5.1 that the greater is the difference in the potential to which the soil was wetted and dried, the greater is the decrease in the strength. Thus it can be suggested that the intensity of wetting and drying influences the end effect of wetting and drying cycles on soil strength. The greater soil water content fluctuation in tilled soil than in non-tilled soil has been discussed in section 6.1. It was therefore suggested that due to a greater intensity of wetting and drying in tilled soil, the decrease in the strength of aggregates in tilled soil will be greater than that of aggregates in non-tilled soil. Thus after the soil has been allowed to wet and dry for several days, the strength of aggregates from the tilled soil may be lower than that of aggregates from non-tilled soil.

It is clear from the previous discussion (section 6.2) that the increase in the amount of wetting and drying was followed by a decrease in clod strength. Likewise, it can be expected that the mean strengths of aggregates collected from soil tilled at different times will be different. Thus aggregates collected from a plot A, tilled earlier, will have a lower strength than those of collected from a plot B, tilled later.

The effect of tillage on aggregate water stability has been widely studied (e.g. Olmstead, 1946; Low, 1972). The general finding is that tillage over a period of years results in a net decrease in aggregate water stability in the few days or weeks after tillage. It seems that this field of study has not received much attention.

Rovira and Greacen (1957) did simulated cultivation in the laboratory to study effects of tillage on aggregate disruption and soil microorganism activity. By using the term "dis-aggregation" (for the definition see section 2.1.1) they found that tillage increases dis-aggregation up to 20 times compared to that of non-tilled soil. Further, they showed that one cycle of wetting and drying increases disaggregation in non-tilled soil. A small decrease in disaggregation was observed in some tillage treatments. However, their observation was not continued over a period of time. This might have provided additional information on any changes in aggregate water stability in the few days after tillage.

After tillage, there are two processes which might occur which could influence aggregate water stability. Firstly, there might be an increase in soil microorganism activity due to tillage treatment (Rovira and Greacen, 1957) or due to alternate wetting and drying (Birch, 1958; Agarwal *et al.*, 1971). Secondly, physical processes might occur as a result of an increase in the intensity of wetting and drying.

The importance of microbial activity on aggregate water stability has been discussed elsewhere (Martin *et al.*, 1955; Harris *et al.*, 1966), and the effect of wetting and drying on aggregate formation and aggregate water stability has been discussed in section 4.

The experiments conducted here were aimed to study changes in the tensile strength and water stability of soil aggregates in the few days after tillage.

6.3.2 Materials and Methods

Aggregate tensile strength

The effect of the intensity of wetting and drying on aggregate tensile strength was studied by testing the tensile strength of soil aggregates collected from tilled and non-tilled plots. This was done on the same plots which were used in the experiment described in section 6.2 (Urrbrae - 1978). At 30 days after tillage (the tilled plot had been wetted and dried to $\Sigma \Delta W$ = 98,8%, and the non-tilled plot to $\Sigma \Delta W$ = 42.0%), 5 kg samples were collected from between the tractor wheel tracks of the tilled plot, and from the non-tilled plot to a depth of about 10 cm. Aggregates of 4.0 - 6.7 mm diameter were separated from these samples by dry sieving. These aggregates were wetted by capillary action, and then subjected to a matric water potential of -100 kPa in a pressure plate apparatus for 2 days.

To obtain additional information, from a different soil, the effects of the amount of wetting and drying on aggregate strength was studied on aggregates collected from Condobolin, N.S.W. This soil has 22% clay, 13% silt, 63% sand, and the soil from the paddocks from which the samples were collected varies from gradational (Gn. 2.12) to duplex (Dr 2.23) (Northcote, 1971). Plot A was tilled six times, i.e. on August 17, 1978 with a disc plough, 3-10-1978 with a scarifier, 22-11-1978 with a disc plough, 9-2-1979 with a rod weeder, 3-4-1979 with a scarifier, and on 1-5-1979 with a scarifier. Plot B was tilled 3 times, i.e. on 3-4-1979 with a disc plough, 1-5-1979 with a scarifier, and on 18-5-1979 with a rod weeder. The samples were collected on May 25, 1979. When the sampling was done, plot A had received 16.6 mm rain since the final tillage, and plot B had received 1.0 mm.

Aggregates with diameters of 4.0 - 6.7, 6.7 - 9.5, and 9.5 - 15 mm were separated from these samples, and subjected to a matric water potential of -153 MPa over saturated $CaCl_2$ solution in a vacuum desiccator for 2 weeks.

The tensile strengths of 20 aggregates of each size range were determined as described in section 5.1.

Aggregate water stability

The experiments were carried out on the Urrbrae (July, 1979) and Strathalbyn (September, 1979) soils. Tillage was done as described in section 6.2. Aggregates of 2.0 - 4.0 mm diameter were collected from between the tractor wheel tracks from depths of 0 - 5 cm, and 5 - 10 cm, at various numbers of days after tillage.

These aggregates were wetted to near saturation by capillary action, and then dried to -10 kPa in sintered funnels for 2 days. The water stability of the aggregates was determined by the wet sieving (see section 4). The aggregates were immersed in distilled water for 5 minutes, and then shaken up and down for 15 minutes.

6.3.3 Results and Discussion

Tensile strength

The results were very interesting. The first experiment (Table 6.17) showed that there was no significant difference in the strength of the aggregates collected from the tilled and non-tilled Urrbrae plots. If the discussion is based only on this result, and the results of the laboratory study (section 5.1, Table 5.8) which show that wetting and drying do not influence the tensile strength of aggregates collected from

Table 6.17. Mean tensile strength of aggregates of 4.0 - 6.7 mm diameter collected from the tilled and non-tilled Urrbrae plots (40 days after tillage).

Aggregate origin	Tensile strength (kPa)
Tilled plot	23.6 (± 4.5)
Non-tilled plot	24.9 (± 3.8)
	N.S.

a non-tilled soil, it would be possible to conclude that wetting and drying do not influence the tensile strength of soil aggregates. This is in contradiction with the other results.

The result of the second experiment, on the other hand, was in good agreement with the hypothesis. Thus the amount of wetting and drying, as shown by the time after tillage, did have an effect on the tensile strength of the aggregates collected from the tilled soil of Condobolin (Table 6.18).

Table 6.18. Mean tensile strength of aggregates collected from the tilled plots at Condobolin.

Aggregate origin	Mean tensile strength (kPa) of aggregates with diameter (mm)			
	2.0-4.0	4.0-6.7	6.7-9.5	9.5-15
Plot A (24 days*)	80.3	57.2	55.7	39.7
Plot B (7 days)	91.8	66.7	55.4	39.6
LSD 5%		10.95		

* refers to the number of days for which the plot had been exposed to wetting and drying since the final tillage.

Further, Table 6.18 shows that the difference in the tensile strength occurs in small aggregates (2.0 - 4.0 and 4.0 - 6.7 mm) but not in the large aggregates (> 6.7 mm). The reason for this phenomenon will be discussed later in this section.

To study further the phenomenon shown in Table 6.17, a similar experiment was conducted in 1979. This was done on the same plot as used in section 6.2 (Urrbrae - 1979). In this experiment the treatment was extended to include the following factors: (1) aggregate diameter (4.0 - 6.7 and 6.7 - 9.5 mm), and (2) aggregate origin (0 - 5 cm and 5 - 10 cm layers of the tilled plot, and 0 - 10 cm layer of the non-tilled plot). The differentiation between the 0 - 5 cm and 5 - 10 cm layers of the tilled plot was based on the (finding discussed in section 6.1), that the fluctuation of soil water content in the 0 - 5 cm layer was much greater than that in the 5 - 10 cm layer. Thus if the intensity of wetting and drying influences aggregate strength, then after the soil is exposed to weathering action for a number of days, the strength of the aggregates from 0 - 5 cm layer would be expected to be lower than that of aggregates from the 5 - 10 cm layer.

The results (Table 6.19) show that the tensile strength of the aggregates from the 5 - 10 cm layer of the tilled plot, especially that for aggregates with diameters of 4.0 - 6.7 mm was greater than that of aggregates from the 0 - 5 cm layer and that from the non-tilled plot. This result demonstrates the importance of the intensity as well as the amount of wetting and drying in decreasing the strength of aggregates in a tilled soil. It can be seen in Figures 6.7 and 6.8 (section 6.1) that the aggregates from the 0 - 5 cm layer were not only wetted and dried more intensively, but after the same number of days after tillage the amount of well-defined wetting and drying they had received, was also greater.

Table 6.19. The tensile strength of the aggregates from 0 - 5 and 5 - 10 cm layers of tilled and 0 - 10 cm layer of non-tilled Urrbrae plots (21 days after tillage).

Aggregate origin	Mean tensile strength (kPa) of aggregates with diameter (mm)	
	4.0-6.7	6.7-9.5
0-5 cm layer (tilled plot)	22.7	18.2
5-10 cm layer (tilled plot)	25.4	19.3
Non-tilled plot	20.0	17.7
LSD 5% :	2.61	

It is likely that tillage tends to increase the strength of individual aggregate. This can be seen from the results given in Table 6.19 which show that the strength of the aggregates from the tilled plot (the 5 - 10 cm layer with diameter of 4.0 - 6.7 mm) was greater than that of aggregates from the non-tilled plot. Due to the increased wetting and drying, the strength of the aggregates from the tilled plot decreased toward the strength of the aggregates from the non-tilled plot. This was shown by the fact that after 21 days of wetting and drying the strength of aggregates from 0 - 5 cm layer was about the same as that of aggregates from the non-tilled plot.

To test this suggestion, experiments were conducted at the Urrbrae (July, 1979) and Strathalbyn (September, 1979) sites. In these experiments, aggregate strength was studied as a function of the amount wetting and drying (the Urrbrae experiment) and as a function of time after tillage (the Strathalbyn experiment).

Tillage was done as described in section 6.2. The soil water content at tillage was 17.8% (Urrbrae) and 17.4% (Strathalbyn). Aggregates of 4.0 - 6.7 and 6.7 - 9.5 mm diameter were collected (at various numbers of days after tillage) from the 0 - 5 cm and 5 - 10 cm layers of the tilled plots, and from the 0 - 10 cm layers of non-tilled plots. These aggregates were wetted by capillary action to near saturated, and then dried to a matric water potential of -100 kPa in a pressure plate apparatus for 2 days. The tensile strengths of 20 aggregates were determined as described before.

The results (Table 6.20 and 6.21) supported the above suggestion. Thus the strength of the aggregates from the tilled plot, especially at 0 days after tillage, was much greater than that of those from the non-tilled plot. These values are 36.1 kPa and 31.4 kPa compared with 21.0 and 25.6 kPa (4.0 - 6.7 mm aggregates), and 28.3 kPa and 25.6 kPa compared with 16.7 kPa and 22.5 kPa (6.7 - 9.5 mm aggregates) for the Urrbrae and Strathalbyn soils respectively. It is possible that the stresses produced by tillage equipment close the cracks which exist in natural aggregates (before tillage), and therefore, yield an increase in the tensile strength of these aggregates. An increase in strength due to the closure of cracks has also been found in coals (Murrell, 1958), rocks (Brace, 1964), and stabilised soils (Ingles and Lafeber, 1967). The increase in the strength of the aggregates with tillage may also be caused by rearrangement of particles within an aggregate. The stresses developed by tillage implements may make the aggregates more dense. This means that the distance between soil particles will become smaller, and the attractive forces, therefore, increase.

It is necessary to point out that these results do not mean that the bulk strength of the tilled soil was greater than that of the non-tilled soil. Although the mean strength of individual aggregates of

Table 6.20. Effect of wetting and drying ($\Sigma\ \Delta\ W$) on the mean tensile strength of aggregates from tilled (0 - 5 and 5 - 10 cm layers) and non-tilled Urrbrae plots.

Days after tillage	Tensile strength (kPa) of aggregates from								
	Tilled plot						Non-tilled plot		
	0-5 cm layer			5-10 cm layer					
	$\Sigma\Delta W$ (%)	4.0-6.7	6.7-9.5[1]	$\Sigma\Delta W$ (%)	4.0-6.7	6.7-9.5	$\Sigma\Delta W$ (%)	4.0-6.7	6.7-9.5
0	0	36.1	28.3	0	36.1	28.3	0	21.0	16.7
2	2.9	29.1	23.9	0.0	34.9	27.7	1.2	20.1	17.6
4	5.9	25.9	23.6	0.2	34.2	25.2	1.5	20.0	17.7
7	9.0	18.5	15.2	0.7	28.9	24.9	3.5	18.5	16.9
11	19.8	19.7	16.0	1.9	25.1	17.7	6.1	19.0	16.2
17	35.4	19.4	16.4	15.8	21.5	16.3	19.9	20.7	16.4
25	42.2	18.9	16.9	21.9	22.1	16.5	26.3	19.3	17.0

[1] refers to aggregate diameter (mm)

Table 6.21. Effect of wetting and drying (time after tillage) on the mean tensile strength of aggregates from the tilled (0 - 5 and 5 - 10 cm layer) and non-tilled Strathalbyn plots

Days after tillage	Mean tensile strength (kPa) of aggregates from					
	Tilled plot				Non-tilled plot	
	0-5 cm layer		5-10 cm layer			
	4.0-6.7	6.7-9.5[1]	4.0-6.7	6.7-9.5	4.0-6.7	6.7-9.5
0	31.4	25.6	31.4	25.6	25.6	22.5
2	26.6	18.7	30.7	24.0	24.3	23.0
4	24.6	18.6	28.9	21.1	26.7	22.8
8	22.5	14.9	25.7	20.5	25.4	21.0
14	19.6	15.8	24.0	15.5	24.4	19.3
21	18.7	15.6	22.1	18.6	24.0	17.2
30	20.4	17.7	21.2	18.7	23.1	18.3

the tilled soil was higher, the bulk strength of the tilled soil is still lower than that of non-tilled soil becuase of the increased macro-porosity.

To obtain a relationship between the amount of wetting and drying and aggregate mean tensile strength, the data were fitted to equation (6.13) for the Urrbrae experiment, and to equation (6.16) for the Strathalbyn experiment. By replacing the term "the proportion, P_δ, of the aggregates larger or smaller than diameter d" with tensile strength, σ_T, these equations become

$$\sigma_{T(\Sigma \Delta W)} = A + a \; [1 - \exp(-a'\Sigma \Delta W)] \qquad (6.20)$$

for the Urrbrae experiment, and

$$\sigma_{T(t)} = A + a \; [1 - \exp(-a't)] \qquad (6.21)$$

for the Strathalbyn experiment.

The resulting values of the parameters A, a, and a' or a" are given in Table 6.22, and the curves of these equations are shown in Figures 6.20 and 6.21.

The larger aggregates had not only a smaller tensile strength, but also a more rapid decrease in the strength caused by wetting and drying. This can be seen from the results in Table 6.18 which shows that the difference in the strengths of aggregates from plot A and B occurs only in the aggregates with diameters smaller than 6.7 mm. A similar tendency is shown in Table 6.19. These results indicate that after a certain amount of wetting and drying the larger aggregates reach an equilibrium value of tensile strength. The smaller aggregates on the other hand, take longer to reach their new equilibrium strength. The more rapid decrease in the strength of the larger aggregates is

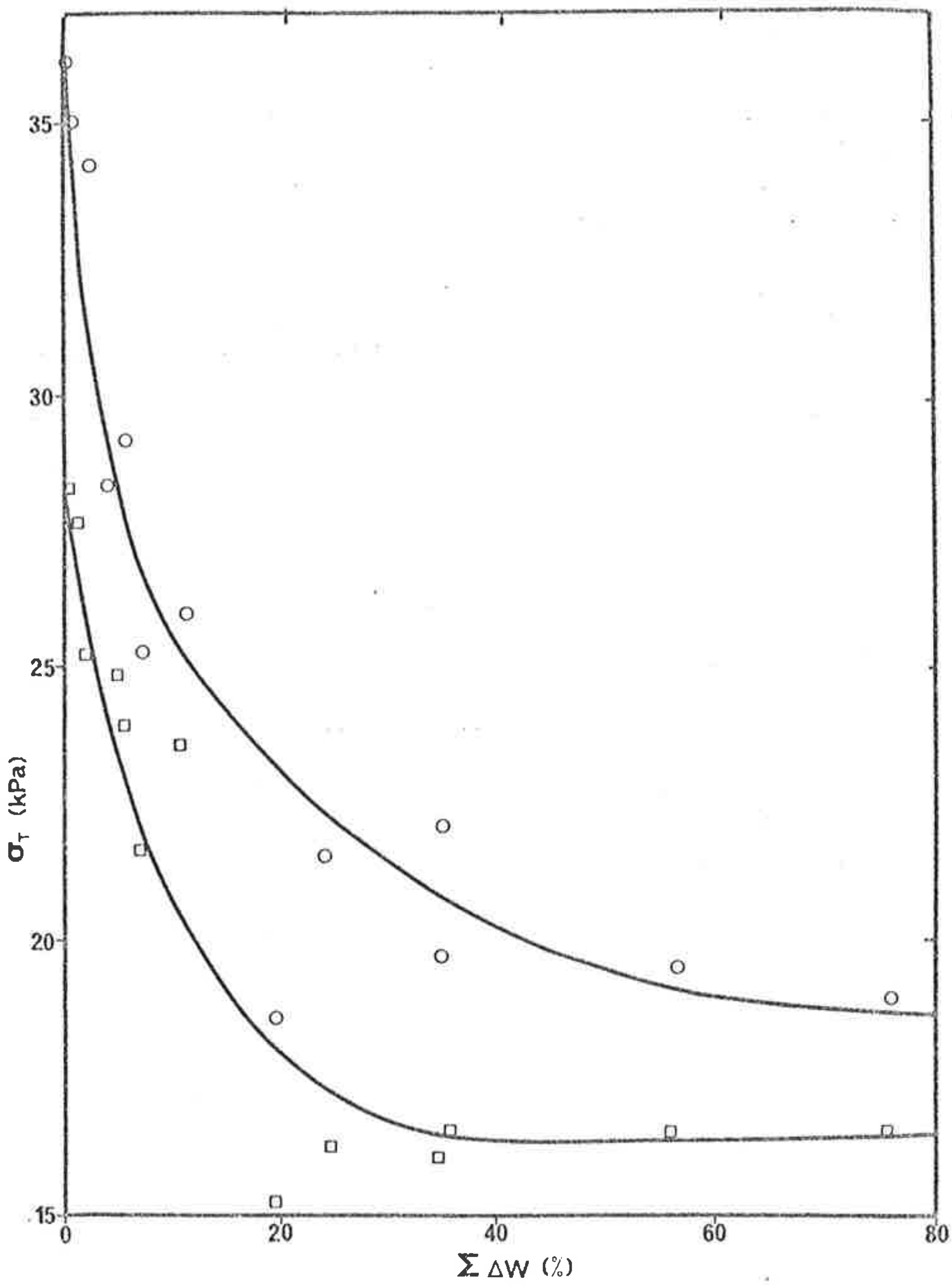


Fig. 6.20. Effect of wetting and drying ($\Sigma\ \Delta\ W$) on tensile strength of the aggregates from the tilled plot of Urrbrae loam. The continuous curves are fit of equation (6.20) and the measurements are given by: (○) 4.0 - 6.7 mm diameter, and (□) 6.7 - 9.5 mm diameter.

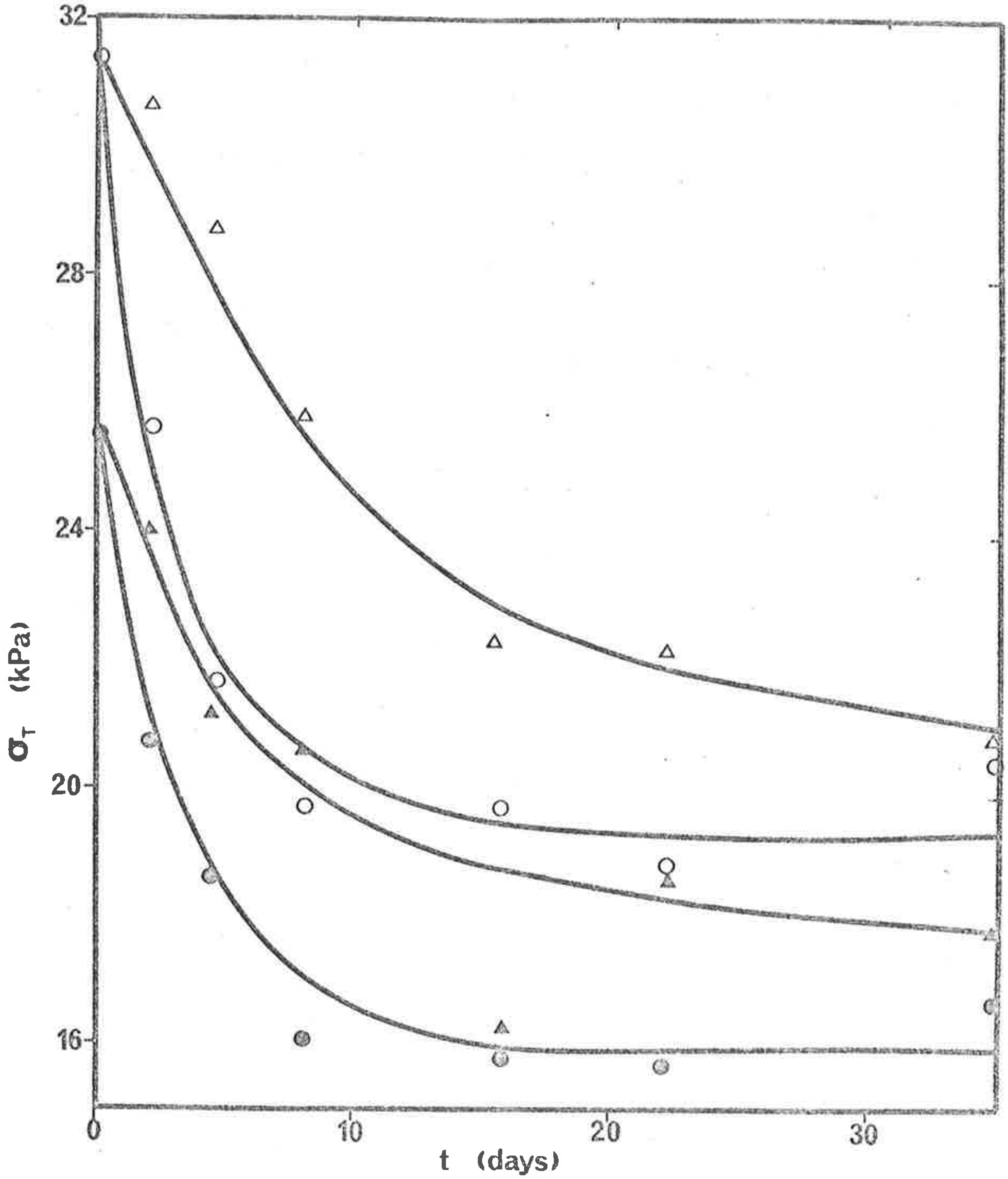


Fig. 6.21. Effect of wetting and drying (as shown by time, t, after the tillage) on tensile strength of the aggregates from tilled plots of Strathalbyn soil.
The continuous curve a fit of equation (6.21), and the measurements are given by (o) aggregates of 4.0 - 6.7 mm from 0 - 5 cm layer, (●) aggregates of 6.7 - 9.5 mm from 0 - 5 cm layer, (▲) aggregate of 4.0 - 6.7 mm from 5 - 10 cm layer, and (▲) aggregate of 6.7 - 9.5 mm from 5 - 10 cm layer.

Table 6.22. The values of parameters of A, a, and a' of equation (6.20) and (6.21) obtained from the Urrbrae and Strathalbyn experiments.

Experiment	Aggregate diameter (mm)	A	a	a'
Urrbrae	4.0-6.7	34.32 (±1.20)	-13.93 (±1.32)	0.24 (±0.02)
	6.7-9.5	27.10 (±1.02)	-11.02 (±1.17)	0.26 (±0.02)
Strathalbyn 0-5 cm layer	4.0-6.7	31.09 (±0.82)	-11.58 (±0.93)	0.02 (±0.04)
	6.7-9.5	25.81 (±0.78)	- 0.79 (±0.87)	0.32 (±0.06)
5-10 cm layer	4.0-6.7	31.78 (±0.45)	-11.17 (±0.75)	0.81 (±0.02)
	6.7-9.5	25.90 (±1.34)	- 8.06 (±1.53)	0.18 (±0.09)

shown more clearly in Tables 6.20 and 6.21; and Figures 6.20 and 6.21. These results are in agreement with the result found in section 5.2, where the reason for this phenomenon has been discussed.

Tables 6.20 and 6.21 also show that the tensile strength of aggregates from the non-tilled plot did not change much with additional natural wetting and drying. It is likely that these aggregates were already close to the equilibrium strength appropriate to their natural wetting and drying regime. This suggestion is supported by the results in Figures 6.20 and 6.21 which show that after reaching a value about the same as that of the tensile strength of the aggregates from untilled plot, further wetting and drying had no or little influence on the tensile strength of the aggregates from the tilled plot.

To study effects of different tillage systems, which result in different intensities of wetting and drying (see section 6.1), samples of aggregates of 2.0 - 4.0 and 9.5 - 15 mm diameters were collected from the Mortlock plots used in section 6.1 to a depth of about 3 cm. When the first sampling was done plots A_W, B_W, C_W and D_W had been exposed to natural wetting and drying for 6, 11, 7 and 11 days (since the final tillage) respectively. The aggregates were air dried, wetted to near saturation by capillary action, and then dried to a matric water potential of -100 kPa in a pressure plate apparatus. The mean strength of 20 aggregates of each size diameter for each treatment was measured as before. The sampling and tensile strength measurement were repeated after the plots had been exposed to further wetting and drying.

The results are given in Table 6.23. Because of interactions of tillage system (which might result in different initial aggregate tensile strengths), the number of days for which the aggregates had been exposed to wetting and drying (after the final tillage), and the intensity of wetting and drying, the results are very difficult to interprete, and is not possible to make a general comparison. If the influence of tillage system on initial aggregate tensile strengh is assumed to be the same, than comparisons could be made between the plots which had been exposed to the same amount or number of days of wetting and drying. Thus aggregates from A_W could be compared with those from C_W, and aggregates from B_W could be compared with those from D_W.

With the assumption that the relative intensity of wetting and drying before observation and during the observation was the same, it can be suggested that the greater is the intensity of wetting and drying, the greater is the decrease in aggregate tensile strength. This can be seen by comparing the tensile strengths of aggregates from A_W and C_W, especially for the aggregates with diameter 2.0 - 4.0 mm (LSD 5% for

Table 6.23. Mean tensile strengths of aggregates of Mortlock soil as influenced by different tillage treatments

Treat-ment	First sampling			$\Sigma \Delta W$ after 1st sampling (%)	Second sampling	
	days after tillage	tensile strength (kPa) 2.0-4.0	tensile strength (kPa) 9.5-15[1]		tensile strength (kPa) 2.0-4.0	tensile strength (kPa) 9.0-15
A_w	6	31.6	18.2	70.45	23.2	12.7
B_w	11	33.7	17.1	38.87	26.2	14.5
C_w	7	35.4	19.1	42.81	24.5	13.6
D_w	11	28.9	16.3	56.30	24.7	12.8
A_p	-	25.0	16.5	11.36	23.8	17.9
D_p	-	24.0	15.4	13.59	22.9	16.0

these two treatments is 2.72). A similar tendency is also found when comparing the tensile strengths of aggregates from B_w and D_w (LSD 5% = 2.59).

In addition, the results in Table 6.22 also support the previous suggestion that tillage tends to increase aggregate tensile strength (as can be seen by the fact that at the first sampling the mean tensile strength of aggregates from tilled plots was greater than that from the non-tilled plot), and due to wetting and drying, this strength decreases toward the equilibrium strength of non-tilled aggregates.

Aggregate water stability

After tillage, there were significant changes in aggregate water stability (Table 6.24). For the Urrbrae experiment, where the independent variable was the amount of wetting and drying, changes in the water stability of aggregates from the 0 - 5 and 5 - 10 cm layers were analyzed altogether. For the Strathalbyn experiment, however, since the independent variable used was time after tillage, the analysis was done separately.

In the first few days after tillage, aggregate water stability increased with wetting and drying (Urrbrae) or time after tillage (Strathalbyn). After reaching a maximum value of stability, it decreased with further wetting and drying or time after tillage (Figures 6.22 and 6.23). The data were fitted to quadratic equations

$$P_{>0.5} = L + l\,(\Sigma\,\Delta\,W) + l'\,(\Sigma\,\Delta\,W)^2 \qquad (6.22)$$

and

$$P_{>0.5} = L + l\,(t) + l'\,(t)^2 \qquad (6.23)$$

for the Urrbrae and Strathalbyn experiments respectively. Here $P_{>0.5}$ is the proportion of water stabile aggregates larger than 0.5 mm, $\Sigma\,\Delta\,W$ is the cumulative wetting and drying, t is the time after tillage. The values of the adjustable parameters L, l and l' are given in Table 6.24. These equations, of course, only represent the results up to $\Sigma\,\Delta\,W$ = 80% and t = 40 days, respectively. It is likely that the stability, as with the tensile strength, also tends towards equilibrium values.

Table 6.24. The values of parameters of L, l and l' of equations (6.22) and (6.23).

Experiment	aggregate diameter before sieving (mm)	L	l	l'	r
Urrbrae	2.0 - 4.0	59.19	0.12	-0.004	0.56
	1.0 - 2.0	49.55	0.51	-0.01	0.77
Strathalbyn	2.0 - 4.0	63.69	1.75	-0.04	0.49
0-5 cm layer	1.0 - 2.0	47.60	2.50	-0.05	0.51
5-10 cm layer	2.0 - 4.0	53.41	1.09	-0.02	0.91
	1.0 - 2.0	33.08	0.66	-0.01	0.76

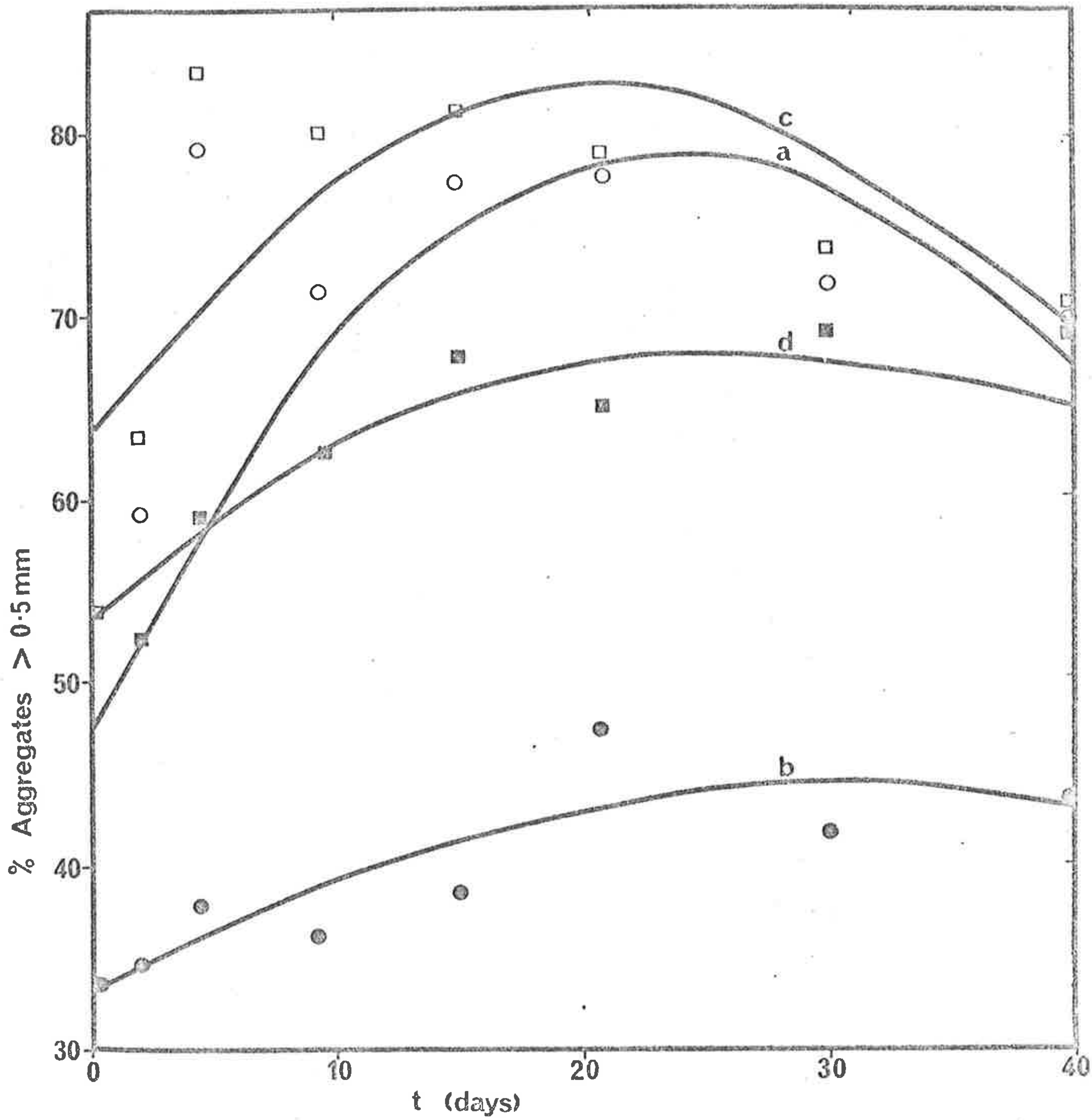


Fig. 6.23. Effect of wetting and drying (as shown by time, t, after tillage) on the water stability of the aggregates from tilled Strathalbyn soil. The continuous curves are fit of equation (6.23). The measurements are given by: Aggregates of 1.0 - 2.0 mm diameter from 0 - 5 cm (○, a) and 5 - 10 cm (●, b) layers. Aggregates of 2.0 - 4.0 mm diameter from 0 - 5 cm (□, c) and 5 - 10 cm (■, d) layers.

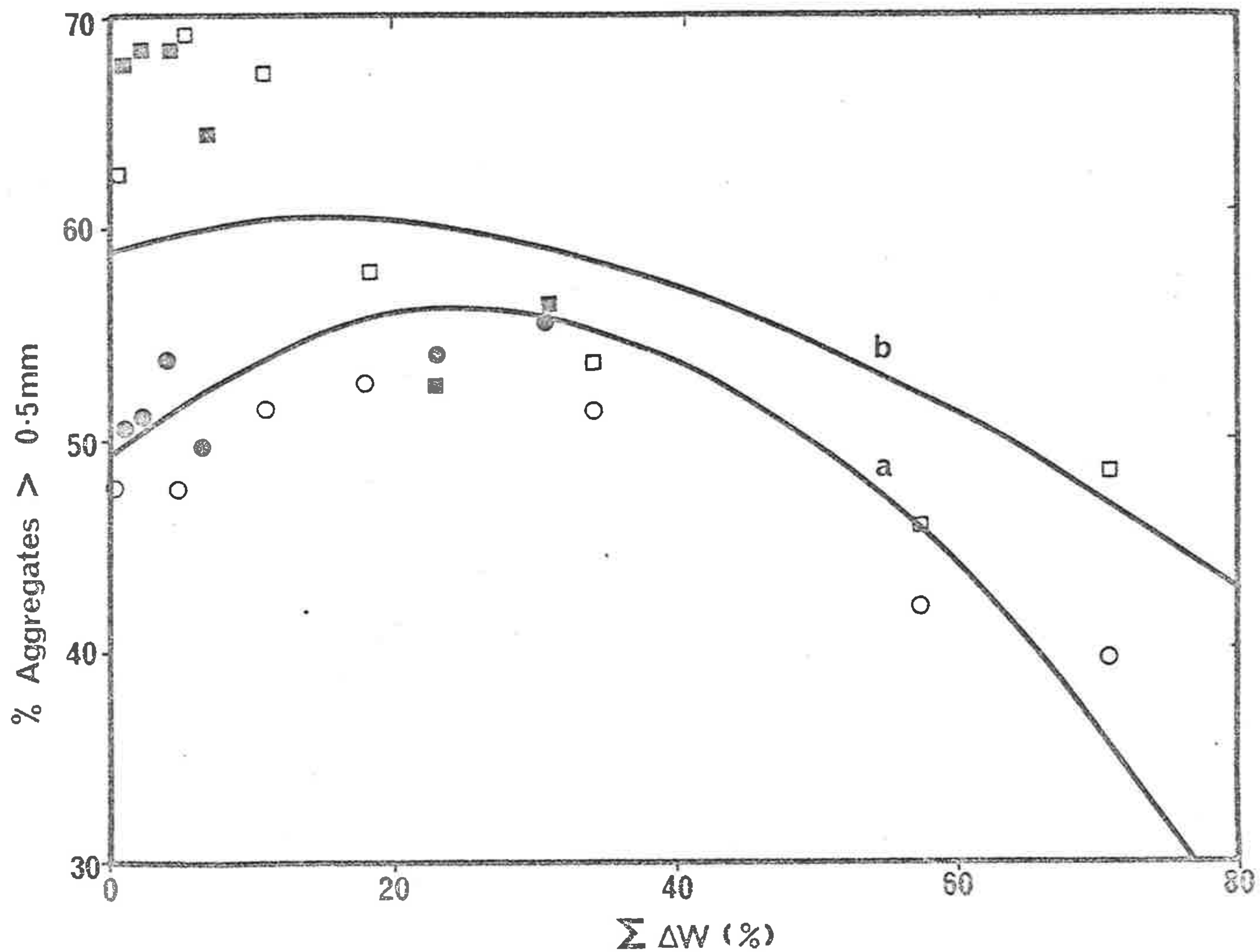


Fig. 6.22. Effect of wetting and drying (Σ Δ W) on the water stability of the aggregates from tilled Urrbrae soil. The continuous curves are fit of equation (6.22). The measurements are given by:

a : aggregates of 1.0 - 2.0 mm diameter from 0 - 5 cm (○) and 5 - 10 cm (●) layers.

b : aggregates of 2.0 - 4.0 mm diameter from 0 - 5 cm (□) and 5 - 10 cm (■) layers.

These changes in aggregate water stability after tillage might have resulted from a combination of the increase in the intensity of wetting and drying, and the activity of soil microorganisms following tillage.

Tillage exposes soil organic matter previously not available to microorganisms (Rovira and Greacen, 1957), and results in an increase in soil microorganism activity. An increase in soil microorganism activity may also occur as a consequence of an increase in the amplitude of natural wetting and drying cycles. The increase in the intensity of wetting and drying with tillage has been discussed extensively in section 6.1, and an increase in microorganism activity with wetting and drying has been demonstrated by many workers (e.g. Birch, 1958; Agarwal *et al.*, 1971; Jagnow, 1972). This is in agreement with the results of the laboratory study (section 4) which showed that in the presence of microorganism activity, wetting and drying up to 3 cycles increased aggregate water stability, and that further wetting and drying cycles decreased aggregate water stability. This did not occur when wetting and drying was done in the absence of microorganism activity (sterilized soil).

The changes in aggregate stability found in this experiment were similar to those found by Monier (1965) in studying the change in aggregate water stability with time after incorporation of organic matter. Monier (1965) suggested that the peak of the curve represents that aggregation brought about by the microbial bodies in the soil. The major factor involved during this period is a mechanical binding action by the mycelia of fungi and actinomycetes, and to some extent of bacterial cells. This type of aggregate stability is only temporary since the mycelia and cells in turn undergo bacterial decomposition as the intensity of the biological action decreases.

The increase in the water stability in the Strathalbyn experiment lasted much longer than that in the Urrbrae experiment (Figures 6.22 and 6.23). These results support the above suggestion. The Strathalbyn soil has a higher soil organic matter content than the Urrbrae soil (2.8% compared to 1.7%). Thus, the Strathalbyn soil can provide a greater source of energy, and hence any increase in soil microorganism activity can persist longer.

Effects of different intensities of wetting and drying resulting from different tillage systems on aggregate water stability were studied on the Mortlock plots (see section 6.1). The results are given in Table 6.25. Again, as with the tensile strength, because of the interaction of the tillage system, the number of days the aggregates had been exposed to wetting and drying, and the intensity of wetting and drying, these results are very difficult to interpret, and a general comparison cannot be made. These data, however, well illustrate that the water stability

Table 6.25. Aggregate water stability of Mortlock soil as influenced by different tillage treatments.

Treatment	First sampling		Second sampling		Third sampling	
	days after tillage	% aggregates >0.5 mm	$\Sigma\ \Delta\ W$ after 1st sampling (%)	% aggregates >0.5 mm	$\Sigma\ \Delta\ W$ after 1st sampling (%)	% aggregates >0.5 mm
A_w	6	78.2	27.36	84.7	70.45	90.0
B_w	11	83.0	11.78	85.7	38.37	85.4
C_w	7	73.7	14.31	82.0	42.81	82.6
D_w	11	79.4	23.24	84.1	56.30	86.3
A_p	-	83.8	6.86	83.6	11.36	83.2
D_p	-	80.9	4.29	83.8	13.59	83.9

Initial aggregate diameter was 2.0-4.0 mm, and the aggregates were immersed in distilled water for 5 minutes, and shaken for 15 minutes.

of soil aggregates differs with different tillage system or with the intensity of wetting and drying. The most important fact found in this experiment is that tillage tends to decrease aggregate water stability (see aggregate water stability at the first sampling), and thus is consistent with the results discussed in section 4. Further, from Table 6.25 it can be seen that the water stability of the tilled aggregates increased with wetting and drying (time) after tillage. This is in agreement with the results for the Urrbrae and Strathalbyn experiments discusses previously.

The organic matter content of the soil did not change significantly with wetting and drying after tillage (Table 6.26). Thus, the changes in aggregate water stability after tillage were not caused by soil organic matter content such as, but rather by their disposition in the soil as has been suggested by Rovira and Greacen (1957).

Table 6.26. Soil organic matter content of Mortlock soil as influenced by different tillage systems.

Treatment	% C at		
	First sampling	Second sampling	Third sampling
A_w	2.08	2.10	2.05
B_w	2.73	2.72	2.54
C_w	2.74	2.74	2.70
D_w	2.91	2.70	2.79
A_p	2.21	2.23	2.21
D_p	3.07	3.01	3.21

6.4 Effect of ageing on the water stability and compression resistance of aggregates disturbed by tillage

6.4.1 Introduction

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

Cooper (1971) suggested that care must be taken not to run over a tilled soil with heavy loads, because a soil which has been broken up and then recompacted is often more dense than it was before tillage. However, he did not describe the reason for this phenomenon. Dexter and Tanner (1974) showed that the soil compression process is time dependent, and can be described by the equation

$$D_t = D_f - \sum_j D_j \exp(-{}^{t}/\tau_j) \qquad (6.24)$$

where

$$\sum_j Dj = (D_f - D_i) \qquad (6.25)$$

Here D is packing density, and the subscripts t, f, and i denote the packing density at time t, final packing density and the initial packing density respectively, and the τ_j are retardation times.

For a soil with packing density, D_t, which is still steadily increasing after the time $t = 10^5$ seconds, the equation used was

$$D_t = P + Q \exp(-t/\tau) + Ct \tag{6.26}$$

with P, Q and C being adjustable parameters.

With these equations, Dexter and Tanner (1974) were able to demonstrate that a remoulded soil compressed much more rapidly than an undisturbed soil. They, therefore, suggested that a soil which has been tilled is more susceptible to compaction than a soil which has not been tilled.

Godwin and Spoor (1977) has observed that tractor sinkage on an undisturbed soil is one third to one quarter to that on a cultivated soil, although, of course, the initial packing density is also smaller in a cultivated soil. However, the lower initial packing density is not sufficient to account for this increased sinkage.

As discussed in section 3.1, together with the increase in the strength of remoulded soil with ageing, which is known as "thixotropic hardening", there is a corresponding increase in the resistance to compression. Evidence for thixotropic behaviour in agricultural soils has also been shown by Blake and Gilman (1970) and Arya and Blake (1972). In studying the water stability of newly-formed aggregates, they found that the water stability increased with ageing. They suggested that this process was analogous to the increase in the strength in remoulded thixotropic soil.

The tensile strength of clods or aggregates in the top (0-5 cm) layer decreases with time after tillage (section 5.1 and 6.3) due to crack formation caused by uneven wetting and drying. The shear strength or penetration resistance, on the other hand, might not be influenced by these cracks (see section 5.1), and might even increase with time after tillage. For the deeper layer (> 5 cm depth), which is dominated by smaller aggregates (Ojeniyi and Dexter, 1979b), ageing after tillage increases aggregate tensile strength. This is because the soil water content fluctuations in this layer are insufficient to cause aggregate cracking. With these strength increases, it can be expected that the resistance of beds of these aggregates to compression also increases. If this is the case, then allowing a tilled thixotropic soil to rest for several days after the first implement pass results not only in a lower cost and energy in tilling the soil (section 6.2), but also in a reduction of compaction damage in the deeper part of the tilled layer (> 5 cm depth).

As suggested in section 3, tillage involves some remoulding and disturbance, then allowing a tilled thixotropic soil to rest for several days before any other operation are performed can increase the strength of the soil.

6.4.2 Materials and Methods

The experiment was conducted on the Urrbrae red brown earth. Tillage was done with a tyne cultivator to a depth of about 10 cm. Water content at tillage was 15.5%.

The extent to which this tillage formed new aggregates or just disturbed and rearranged the existing ones is now 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 with diameters of 1.0 - 2.0 mm were separated from this sample by dry sieving. Sub-samples of these aggregates were used to determine aggregate water stability and the resistance of beds of these aggregates to compression. The remainder were stored at constant water content for later testing. To do this, the 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 (see section 4). 20 g of aggregates were immersed in distilled water for 5 minutes, and then shaken up and down for 5 minutes. Aggregate water stability was calculated as the final percentage of aggregates larger than 0.5 mm diameter. 3 measurements were done for each ageing time.

The compression test on beds of these aggregates was done in a standard consolidometer (see section 3) with uniaxial stresses of 0, 2.5, 4.9, 9.8, 14.7, 19.6 and 29.4 kPa.

6.4.3 Results and Discussion

Aggregate water stability

It was found that the water stability of the aggregates disturbed by tillage from Urrbrae red brown earth increased with ageing time (Figure 6.24). The data were fitted to equation (6.13). By introducing the term "stability, S_t, at time t", the equation was

$$S_t = \underset{(\pm 1.69)}{46.61} + \underset{(\pm 2.04)}{12.07} \left[1 - \exp\left(\underset{(\pm 0.09)}{-0.19}\ t\right)\right] \qquad (6.27$$

Several processes might be involved in causing this increase. There is no doubt that the presence of organic matter as an energy source is one of the important factors responsible for this increase. So is the contribution of soil microorganisms as discussed in Section 6.3.

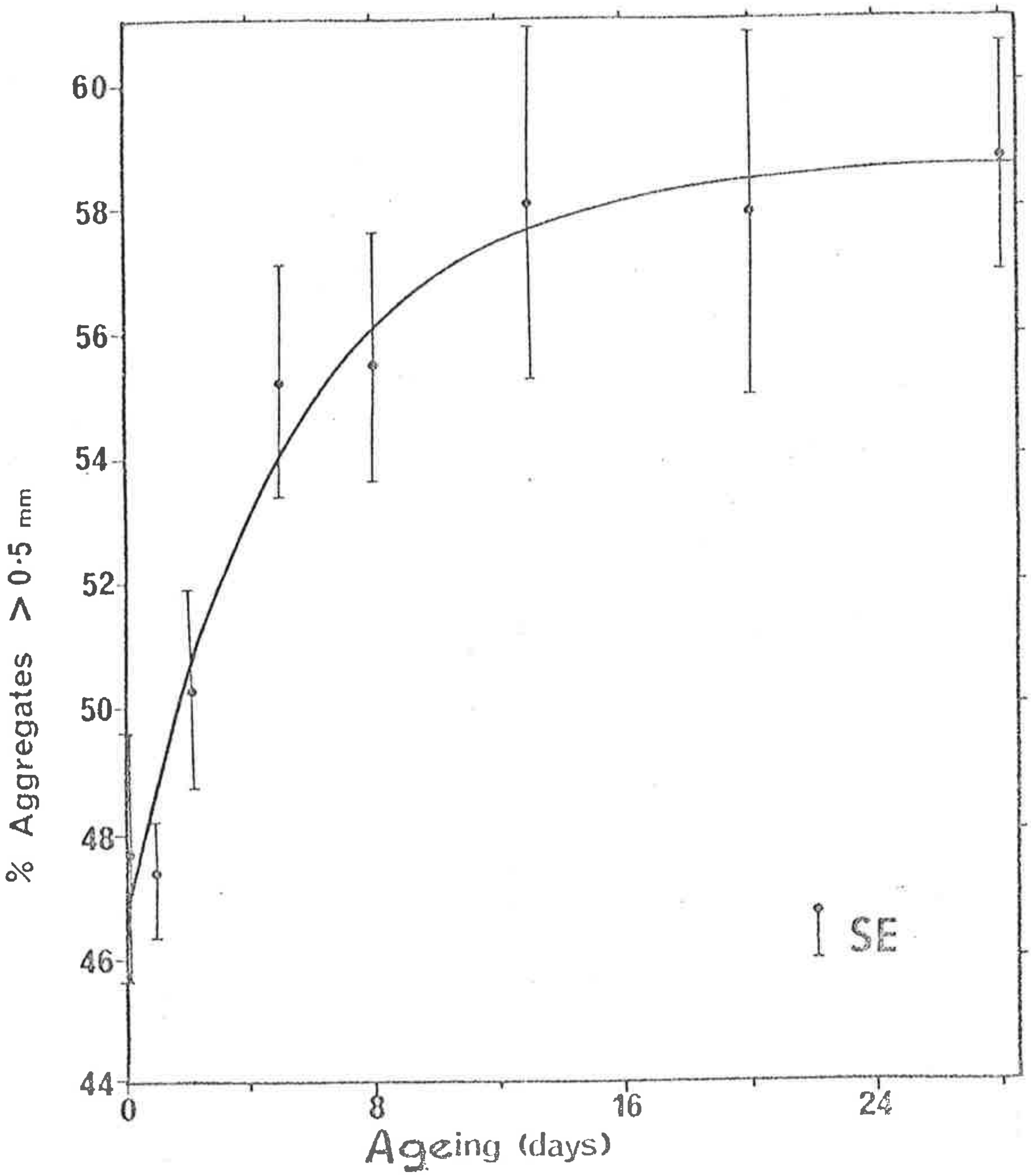


Fig. 6.24. Effect of ageing since disturbance on the stability of aggregates of Urrbrae loam. Circles are means of three measurements. The curve is from equation (6.27).

Without ignoring the importance of these factors, Blake and Gillman (1970) suggested that the increase in water stability of newly formed aggregates with ageing is a thixotropic process. It was shown that in the absence of organic matter there is still an increase in aggregate water stability.

From thixotropic point of view, it can be suggested that tillage disturbed and probably formed new aggregates. Soil shearing and compression produced by the tillage implement may cause some rearrangement of the platy clay particles into a uniform, parallel arrangement. When the tillage implement has passed, the external forces which assist the repulsive forces drop to zero, and now the attractive forces in the system are much greater. With this condition, the structure tends to adjust to an equilibrium state with a more random arrangement. Together with this change, there is a corresponding increase in interparticle attraction, Blake and Gilman (1970) suggested that this interparticle attraction and linkage tends to make the aggregates resist slaking.

Compression resistance

Together with the increase in aggregate water stability, there was an increase in the resistance of beds of these aggregates to compression (Figure 6.25). The data was fitted to equation (6.24), with the uniaxial stress, S, replacing the time t:

$$D_s = D_f - D_m \exp(-S/m) \qquad (6.28)$$

The resulting values of the parameters D_f, D_m and m are given in Table 6.26.

It can be seen from Table 6.27 that ageing decreased the maximum packing density from 0.791 (0 day sample) to 0.668 (6 days aged sample).

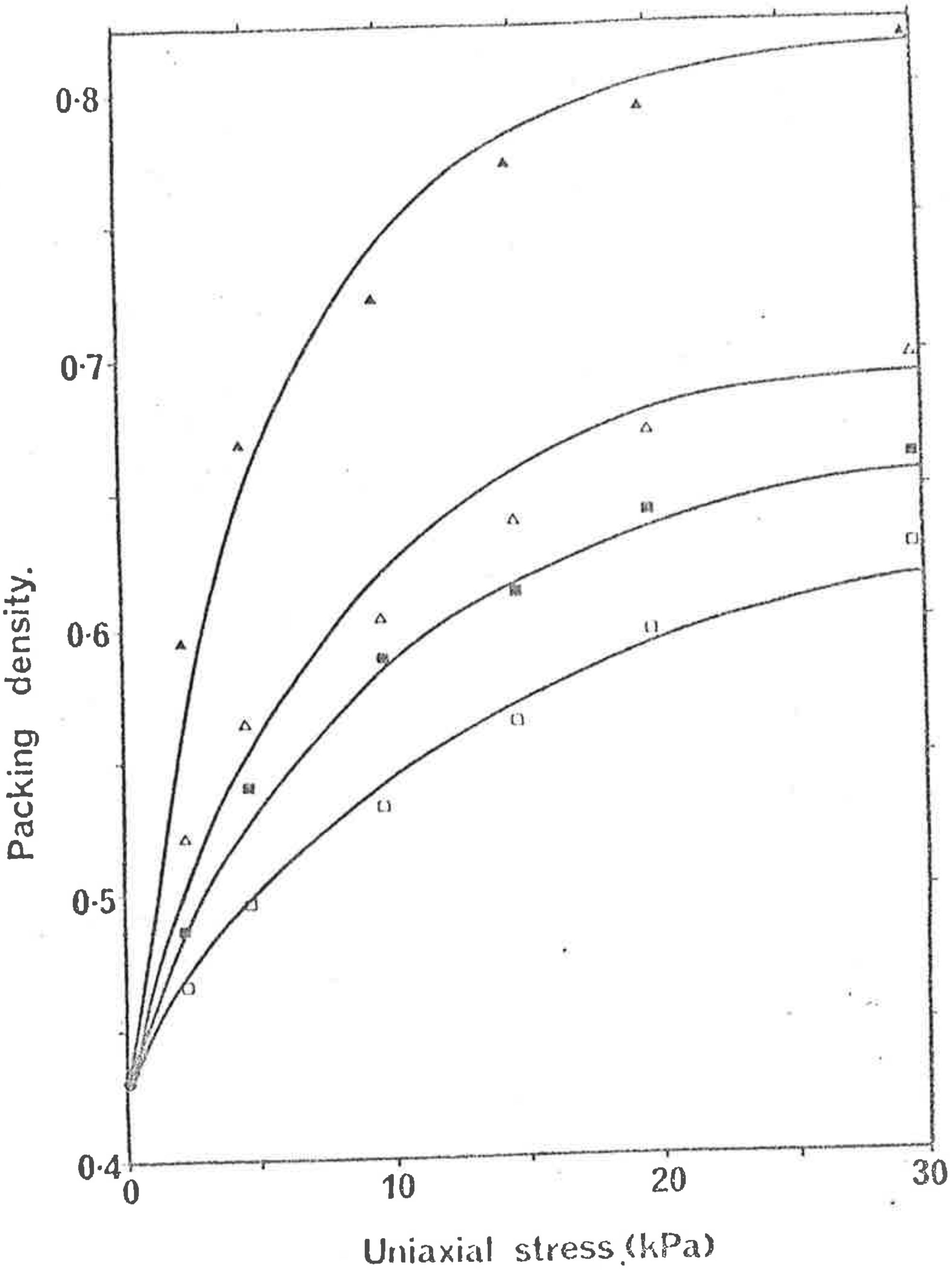


Fig. 6.25. Effect of ageing on the resistance of beds of disturbed aggregates to compression (Urrbrae soil). Points are measurements. The curve is from equation (6.28). The measurements are given by: ▲ : 0 days; △ : 3 days; ■ : 6 days and □ : 10 days aged.

Table 6.27. The values of parameters of D_f, D_m and m of equation (6.28) resulting from compression tests on beds of aggregates of Urrbrae soil aged for different periods of time since disturbance by tillage.

Ageing (days)	D_f	D_m	m (kPa)
0	0.791 (±0.018)	0.344 (±0.025)	5.24 (±1.22)
3	0.700 (±0.021)	0.251 (±0.020)	9.15 (±2.32)
6	0.688 (±0.009)	0.231 (±0.009)	9.28 (±1.11)
10	0.681 (±0.016)	0.245 (±0.015)	18.96 (±2.48)

This indicates that the aged samples compress less than the non-aged samples. In addition, as discussed in section 3.2 that m is the most important parameter controlling the compression resistance. It can be seen in Table 6.26 that ageing also increases the value of m, which indicates that the increase in packing density (towards a final equilibrium packing density) with applied stress in the aged sample occurs more slowly than in the non-aged sample.

Day and Holmgren (1952) and McMurdie and Day (1958) showed that the volume changes during compression of beds of moist soil aggregates are attributable to plastic deformation. This can be seen by the development of flat interfaces at the points of contact between aggregates which are still evident at the end of compression test. At low soil water contents, Dexter (1975) suggested that compression occurs as a result of aggregate rupture. Kezdi (1979) proposed that the compaction of a cohesive soil occurs in two steps. Firstly, the soil aggregates have to be broken up in order to eliminate the secondary (macro-) pores in the loose mass, and secondly, the decrease in the volume of primary pores.

In this experiment, soil water content was 15.5%, and it is likely that the change in packing density was mainly caused by aggregate rupture and the decrease in the volume of primary pores.

It was thought that the increase in the strength of remoulded aggregates (section 3) occurs also in the aggregates disturbed by tillage. As has been shown by Braunack and Dexter (1978), an increase in the tensile strength of the individual aggregates will result in an increase in the resistance of beds of these aggregates to compression. Thus, it is reasonable to suggest that ageing can increase the compression resistance. The process by which ageing increases soil strength has been extensively discussed in section 3.

A further experiment was designed to test the extent to which this behaviour occurs when tillage is done at different soil water contents, especially those close to the optimum soil water content for tillage. As was predicted by the soil friability measurement (section 5.2), which is in good agreement with the results of Ojeniyi and Dexter (1979a), the optimum soil water content for tillage for the Urrbrae fine sandy loam is around 17% (or 0.9 of the Plastic limit).

In addition, it is interesting to discuss Dexter and Tanner's (1974) suggestion that remoulded soil compresses more rapidly than undisturbed soil (see equation 6.24). With this equation, the resistance to compression can be seen both from the final packing density and the time for compression. So, if ageing increases the resistance of the soil to compression it will probably also result in an increase in retardation time of the compression process. Dexter and Tanner (1974) have pointed out the importance of compression time in controlling the compaction problem, and suggested that a retardation time of about 10^3 s would be an advantageous for agricultural soils.

Because of the weather, it was not possible to do tillage exactly at the optimum soil water content. The soil water content at tillage was W = 19.3%. At this water content, it was very difficult to sieve aggregates of 1.0 - 2.0 mm diameter. So, unlike in the previous experiment, the aggregates used here had diameters in the range 1.0 - 4.0 mm.

To provide information from another soil, an additional experiment was done at the Charlick Experimental Station at Strathalbyn. Some properties of this soil have been described in section 3. As in the Urrbrae experiment, tillage was done with a tyne cultivator to a depth of about 10 cm. The soil water content at tillage was W = 19.2%. The aggregates used for the compression test had diameters in the range 1.0 - 4.0 mm.

The variation of packing density with time could not satisfactorily be described by a single exponential equation, so they were fitted to the double exponential equation

$$D_t = D_f - D_l \exp(-t/_{\tau l}) - D_n \exp(-t/_{\tau n}) \qquad (6.29)$$

The resulting parameters D_f, D_l, D_n, $_{\tau l}$, and $_{\tau n}$ are given in Table 6.28 for the Urrbrae experiment, and in Table 6.29 for the Strathalbyn experiment.

As expected, the results (Tables 6.28 and 6.29) show that ageing not only decreased the final equilibrium packing density, but also increased the time for compression. The 1 day aged Urrbrae soil (Table 6.28 and Figure 6.26) had retardation times of $_{\tau l}$ = 5.6 and $_{\tau n}$ = 149 s, whereas the 10 days aged sample had retardation times of $_{\tau l}$ = 8.0 s and $_{\tau n}$ = 383 s. For the Strathalbyn soil (Table 6.29 and

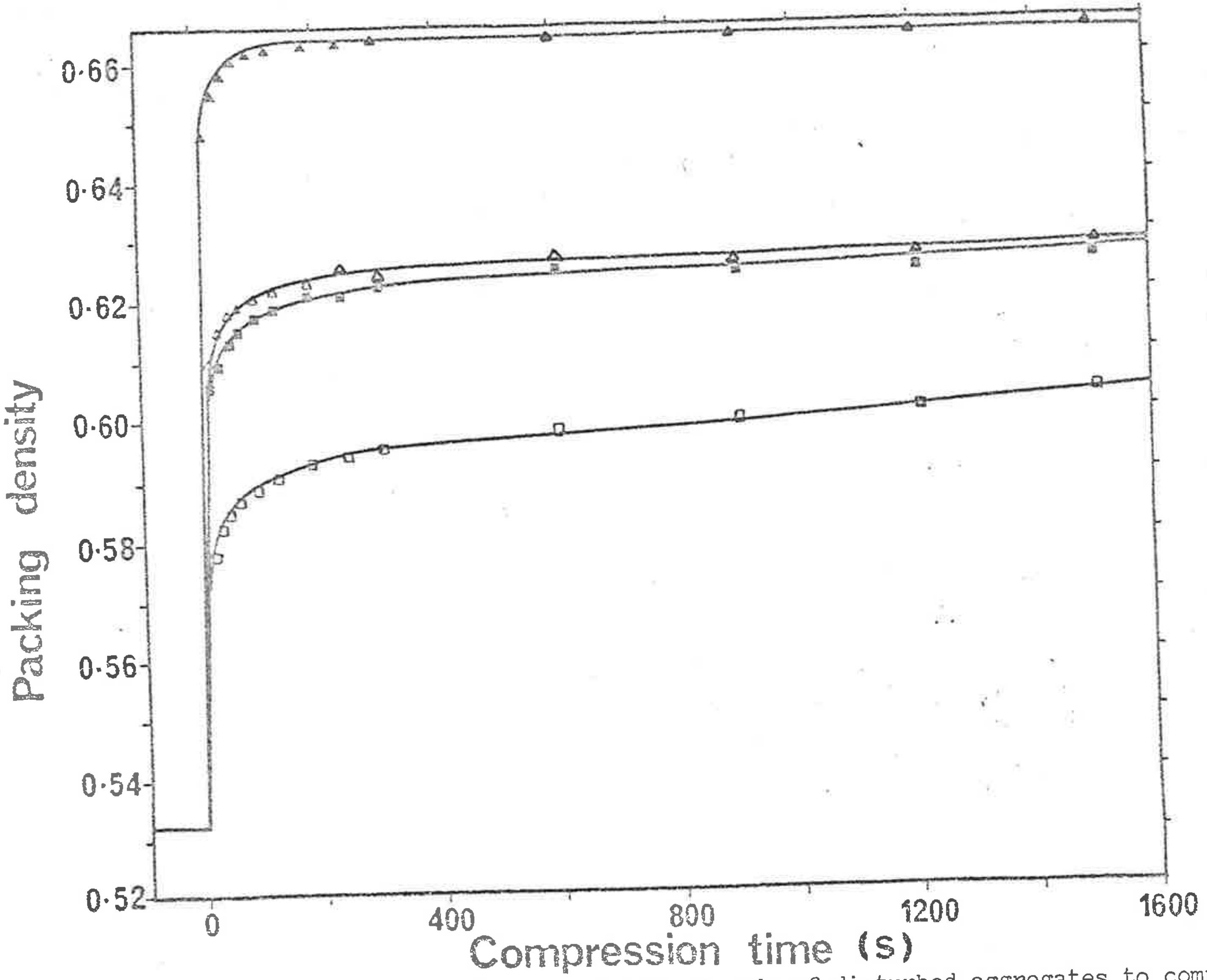


Fig. 6.26. Effect of ageing on the resistance of beds of disturbed aggregates to compression (Urrbrae soil). The continuous curves are fit of equation (6.29). The measurements are given by: ▲ : 0 days; △ : 2 days; ■: 4 days and □ : 10 days aged.

Table 6.28. The values of parameters D_f, D_1, D_n, τ_1, and τ_n of equation (6.29) resulting from compression tests (29.4 kPa stress) on beds of aggregates of the Urrbrae soil aged for different times.

Ageing (days)	D_f	D_1	D_n	τ1(s)	τn(s)
0	0.664 (±0.001)	0.106 (±0.000)	0.025 (±0.000)	0.80 (±0.35)	27.88 (± 1.08)
2	0.627 (±0.000)	0.082 (±0.001)	0.013 (±0.000)	5.60 (±0.30)	149.07 (±18.18)
4	0.627 (±0.000)	0.079 (±0.002)	0.016 (±0.001)	5.20 (±0.70)	246.26 (±55.74)
10	0.603 (±0.001)	0.052 (±0.002)	0.018 (±0.001)	8.01 (±1.00)	383.58 (±125.91)

Table 6.29. The values of parameters D_f, D_1, D_n, τ_1, and τ_n of equation (6.29) resulting from compression tests (29.4 kPa stress) on beds of aggregates of the Strathalbyn soil aged for different times.

Ageing (days)	D_f	D_1	D_n	τ1(s)	τn(s)
0	0.657 (±0.001)	0.138 (±0.002)	0.020 (±0.001)	2.20 (±0.19)	193.93 (±52.50)
1	0.651 (±0.002)	0.128 (±0.003)	0.025 (±0.002)	3.79 (±0.34)	201.26 (±69.53)
3	0.624 (±0.001)	0.105 (±0.005)	0.020 (±0.004)	3.76 (±0.52)	112.60 (±53.20)
7	0.617 (±0.000)	0.101 (±0.002)	0.108 (±0.001)	3.21 (±0.21)	212.60 (±51.95)
14	0.581 (±0.000)	0.069 (±0.001)	0.013 (±0.001)	3.77 (±0.23)	179.37 (±40.64)

Figure 6.27) the retardation times for the non-aged samples were τ_1 = 2.2 s, and τ_n = 193 s, whereas the retardation times for 7 days aged samples were τ_1 = 3.7 s and τ_n = 212 s. It seems that these values are small, but it must be realized that a soil is stressed by tractor tyres for around 5 X 10^{-5} s, and by animal feet for around 10^0 - 10^2 s (Dexter and Tanner, 1974). Together with the decrease in the final equilibrium packing density, these increases in retardation times could have some influence on soil compaction in the field.

With soil water contents of W = 19.3% (Urrbrae) and 19.2% (Strathalbyn) (each slightly above the plastic limit), it can be expected that compression mainly 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 as could be seen by the occurrence of flat interfaces at points of inter-aggregate contact as drawn schematically by Davies *et al.* (1973) there was some rupture of some aggregates. This result demonstrates that even at the plastic limit, the aggregates disturbed by tillage from the Urrbrae and Strathalbyn soils can exhibit brittle behaviour. Braunack and Dexter (1978) found that even with water matric potentials as close to saturation as -1 kPa (corresponding to a water content of about W = 30%), natural aggregates from the Urrbrae fine sandy loam can still behave as a brittle material under tensile stress.

Plastic deformation can only occur if the applied stress overcomes the shear strength of the soil, and aggregate rupture occurs when the applied stress overcomes the tensile strength of the aggregates. Thus by considering the process by which compression occurs, it can be thought that the increase in the compression resistance of beds of aggregates found in this experiment resulted from the increase in the shear strength and in the tensile strength of aged aggregates.

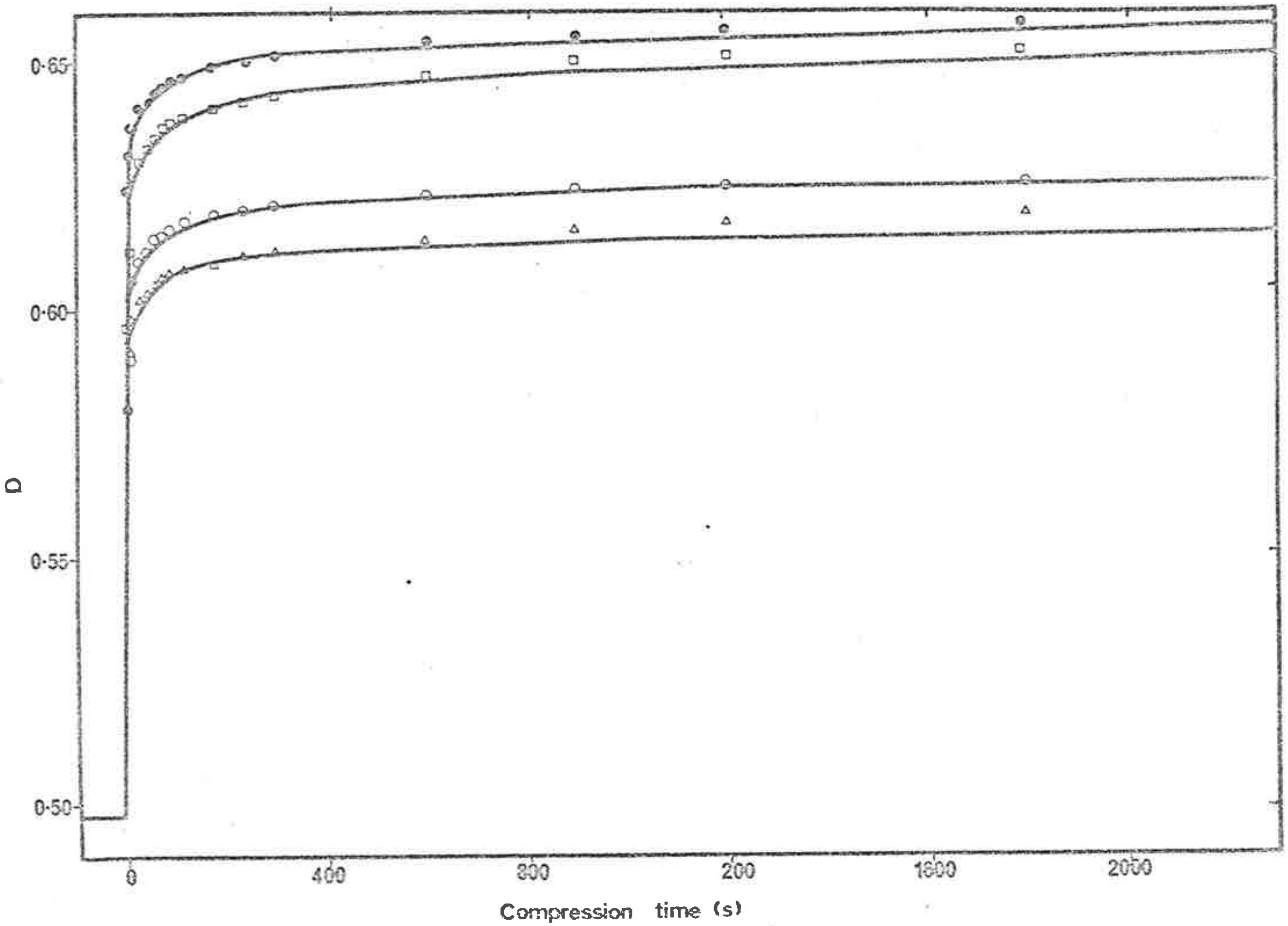


Fig. 6.27. Effect of ageing on the resistance of beds of disturbed aggregates to compression (Strathalbyn soil). The continuous curves are fits of equation (6.29). The measurements are given by: ● : 0 day; □ :1 day; ○ : 3 days and △ : 7 days aged.

Based on the result discussed above, it can be suggested that allowing a thixotropic soil to rest for several days after tillage before any other activity is performed can reduce both compaction damage and the aggregate breakdown risk.

6.5 Conclusions

The experimental results discussed above have demonstrated that the amplitude as well as the rates of wetting and drying are greater in tilled soil than in non-tilled soil. Different tillage systems can result in different amplitudes of soil wetting and drying.

Meteorological factors have an important role in controlling drying from a soil when soil water content is high enough to provide the evaporative demand. When soil water content is low (about $W = 10\%$ for the Urrbrae fine sandy loam), the rate of drying is mainly controlled by soil water content.

In the Spring, the meteorological factors which influence drying from a soil were radiation and temperature. Wind speed had only a slight effect. In the Winter, however, the role of radiation and temperature are less important, and wind speed is more important.

Relative humidity influences soil drying when the soil water content is high enough to provide the evaporative demand (Urrbrae - 1978). As soon as the soil water content decreases (1978 exp. 2, and 1979 exp.), the influence of relative humidity becomes insignificant.

Natural wetting and drying decreases the strength of the clods produced by tillage. This is shown both by the decrease in the energy required to break the clods, and in the tensile strength of soil aggregates produced by tillage. The decrease in clod strength is also shown by the fact that the proportion of the smaller aggregate fraction produced by the second implement pass is greater after the soil has been allowed to wet and dry naturally for several days than when it is done straight away after the first implement pass. An increase in the proportion of the smaller aggregate fraction has also been shown to be caused by the direct action of wetting and drying.

It has been found that in the first few days after tillage, there is an increase in aggregate water stability. It is suggested that the increase in aggregate water stability in the top tilled layer is a result of a combination the increase in the amplitude of soil water content fluctuation and an increase in soil microorganism activity. The increase in water stability of the aggregates from the deeper layers of the tilled soil is attributed to a thixotropic process.

In the laboratory, it was found that ageing the aggregates disturbed by tillage increases the resistance of beds of these aggregates to compression. This was shown both by the decrease in the final equilibrium packing density and by the increase in the time for compression.

It is suggested that it would be a good idea to delay a second implement pass a few days after the first implement pass. By doing this, it can be expected that soil can be tilled with minimum cost and energy to produce a good seed bed. In addition, due to an increase in aggregate water stability and in the compression resistance, it can be expected that the compaction problem and aggregate breakdown risk can be minimized.

SECTION 7

GENERAL DISCUSSION AND CONCLUSIONS

7.1 Introduction

As discussed in section 1, the main objective of the investigations described in this thesis is to study any changes in soil physical properties resulting from soil management practices, and then to relate these changes back to soil management systems. It is expected that at least some of the results which have been obtained can be applied to develop soil management systems which allow the production of food crops at minimum cost, and which at the same time, minimize soil deterioration caused by unnecessary removal of plant nutrients, erosion and compaction.

Much effort has been put into attempts to achieve efficient soil management systems. History has proven that while we have been successful in our attempts to increase crop yield per unit area in a good soil, we have fallen behind in our attempts to maintain the condition of the soil. As suggested in section 1, one of the reasons for this is probably the limited information available on the effects of soil management systems on soil physical properties. Consider, for example, tillage. This is one of the oldest branches of agricultural science, and probably one of the most intensively studied. In spite of this, soil physical property changes caused by this form of soil management, especially any changes in the period immediately after tillage, have not been studied in any detail. Some farmers have for a long time believed that allowing a soil to wet and dry naturally for several days after a first implement pass enables the soil to be more easily broken in a subsequent tillage operation (Jones *et al.*, 1941; Woodburn, 1944; Fountaine *et al.*, 1956). For this phenomenon

Sir E.J. Russell (1957) wrote "for making the crumbs, the operative agents are climatic, and the purpose of cultivation is to put the soil into such condition that they can act most efficiently ..... the alternate wetting and drying affected by the rain and wind prompts the formation of stable crumbs; the resulting swelling and contractions cause cracks which weaken the clods and if now they are struck by a hoe or harrow while just sufficiently moist, they fall into smaller fragments which can be further worked down". It seems this is a common assumption, and yet there has been little or no attention given either to the acquisition of quantitative data or to the elucidation of the mechanisms involved in this important phenomenon. If the changes and the mechanisms by which the changes in soil physical properties can be understood, then it might be possible to make use of these effects in the development of new soil management systems.

The results discussed in section 3, 4, 5 and 6 have shown that these management systems can be attained by simple and nonexcessive means. In this section, an attempt is made to discuss all the results together, and to combine or to relate them to each other to obtain a comprehensive soil management system. Some suggestions for further research are also made.

7.2 Discussion and Conclusions

It has been shown (section 6) that tillage modifies soil water behaviour, and influences both the water stability and the tensile strength of soil aggregates.

Tillage influences both the amplitude of soil water content fluctuation (wetting and drying) and the mean soil water content. The rate of drying of the tilled layer of tilled soil is greater than that of the same layer of non-tilled soil because of a better water/vapour conductivity (Gardner, 1958), penetration of turbulent air (Hanks and Woodruff, 1958; Holmes *et al.*, 1960), and downward movement of water/vapour due to a higher mid-day temperature gradient (De Vries, 1963; Allmaras *et al.*, 1977; Hay, 1977). The greater wetting rate in tilled soil has been suggested to be caused by a greater rain water infiltration due to the greater surface roughness (Burwell *et al.*, 1966; Dexter, 1977; Johnson *et al.*, 1979), a greater water movement from the deeper layer (the layer beneath the tilled layer), and a greater water condensation due to a colder surface temperature at night time (van Duin, 1954). Under South Australia conditions, until 20 days after tillage, the cumulative wetting and drying ($\Sigma\ \Delta$ W) in the tilled layer (0 - 10 cm depth) of tilled soil was greater by a factor of 1.7 - 2.0 compared with that in the same layer of non-tilled soil. This magnitude was influenced by the system and the intensity of tillage. It was found that the cumulative wetting and drying ($\Sigma\ \Delta$ W) in the top layer (0 - 3 cm depth) of tilled soil was greater by factors of 5.6, 3.1, 3.4, and 4.5 for soil which was managed by direct drilling with a combine drill fitted with 5 cm lucerne points on sowing; by a rotary seeder and compaction roller; by a scarifier, harrow, combine and harrow; and by a Howard rotary seeder, harrow, rotary seeder, compaction roller; respectively.

It was found (section 6.1) that meteorological factors have an important role in controlling the rate of drying when soil water content is high enough to provide the evaporative demand. When soil water content is low (below about 10% for the Urrbrae fine sandy loam), the rate of drying is mainly controlled by soil water content. In the Spring, the meteorological factors which influence the rate of drying are radiation and temperature. Wind speed has only a small effect.

In the Winter, however, the role of radiation and temperature is less important, and wind speed becomes more important. Relative humidity influences the rate of drying when soil water content is high enough to provide the evaporative demand. As soon as the soil water content decreases to a value that cannot meet the evaporative demand, the influence of relative humidity becomes insignificant.

Due to the breakdown of interparticle bonds, soil disturbance by tillage decreases aggregate water stability (sections 4 and 6). Wetting and drying after tillage give rise to an increase in aggregate water stability. It has been suggested that the increase in aggregate water stability (> 0.5 mm) in the top layer of a tilled soil results from a combination of increasing soil water content fluctuations (due to tillage) and of increasing soil microorganism activity.

The activity of soil microorganisms increases (after tillage) because there is an extra energy source from soil organic matter which was previously not available (Rovira and Greacen, 1957), and is stimulated by wetting and drying (Birch, 1958; Agarwal *et al.*, 1971). This suggestion is supported by the fact that after reaching a maximum value of water stability (after which the organic matter is thought again to become a limiting factor), aggregate water stability decreases with time or wetting and drying (section 6.3). The results of a laboratory experiment discussed in section 4 show that in the absence of micro-organism activity (sterilized soil), wetting and drying aggregates which had been disturbed by tillage resulted in a steady decrease in their water stability in agreement with the above suggestion. The increase in aggregate water stability in the deeper layer, in which diurnal soil water content fluctuations are negligible, was suggested to be mainly a thixotropic process.

With these findings, it is suggested that an increase in the water stability of aggregates disturbed by tillage can be achieved by providing an extra energy source for soil microorganism activity. The microorganisms can then replace the interparticle bonds (by exudation, etc.) which have been destroyed by tillage. This extra energy source can be obtained, for example, by incorporating plant residues during tillage. By doing this, it can be expected that soil organic matter will not become a limiting factor so soon, and therefore, that aggregate water stability will not begin to decrease so rapidly. In this case, aggregate breakdown risk, and run off with its consequence of erosion, which usually occurs before complete crop cover is attained, can probably be minimized.

The finding that wetting and drying cycles can assist the formation of soil aggregates (in nonaggregated soils) might be useful in the restoration of some structurally degraded soils. The relatively greater amplitude of soil water content fluctuations in tilled compared with non-tilled soil, or on stubble burnt compared with stubble retained managements before tillage (Hewitt and Dexter, 1980), can increase the formation of planes of weakness. The soil can then be more readily broken down into a suitable structure. .It is important to remember that as discussed in section 2.1.4, tillage can have a much higher efficiency if it makes use of existing planes of weakness in the soil. This will be discussed further later in this section when discussing soil friability.

To obtain water stable aggregates, wetting and drying cycles alone are not sufficient. As shown in section 4, the existence of micro-organism activity in the soil is necessary to produce these water stable aggregates. Hence, the incorporation of plant residues in tillage practice will not only stabilize the small aggregates which have been formed by tillage, but will also stabilize those aggregates formed by wetting and drying which are still held in large clods, so that when these clods are broken, they break into smaller water stable aggregates.

In section 5.1, it has been shown that wetting and drying may decrease the strength (drop shatter and tensile test) of remoulded and field aggregates. In field experiments (section 6.2), it was found that as a result of increasing the amplitude of wetting and drying (section 6.1), the strength of clods produced by tillage decreased with wetting and drying cycles. This was shown by the fact that with the same applied energy (in the drop shatter test), clods which have been subjected to natural wetting and drying cycles break up more than clods which have been recently formed and thus which have not been subjected to increased wetting and drying. The results of tillage experiments (section 6.2) show that, under South Australian conditions, when a second implement pass is done a few days after the first implement pass a greater proportion of smaller aggregates are produced than when tillage is done straight away after the first implement pass. This tilth mellowing effect is attributed to the effects of the increase amplitude of wetting and drying cycles in the tilled soil relative to that in the non-tilled soil. Based on this finding, it is suggested that it is worthwhile to delay a second implement pass for several days to allow the natural wetting and drying cycles to weaken the clods by forming internal micro cracks. The clods can then be broken more easily by the mechanical impact of a tillage implement. If this is the case, then the soil can be tilled with minimum cost and energy to produce a good seed bed. In addition, with decreasing clod strength, it may be possible to reduce the number of implement passes, so that the compaction problem caused by the weight of the tractor and implement can be minimized.

It has been found (section 3.1) that some agricultural top soils exhibit appreciable thixotropic behaviour around the water contents at which tillage is usually performed. Ageing these remoulded soils results in an increase in their strength. In this thesis, this is shown by increases in shear strength, penetration resistance, tensile strength, and compression resistance. The water content at which the maximum thixotropic strength ratio occurs is influenced by the type of clay minerals in the soil. For soils containing kaolinite (in this thesis Urrbrae and Mortlock red brown earth), the maximum thixotropic strength ratio occurs at a water content around the plastic limit. For soils containing montmorillonite or illite, but not containing any kaolinite (in this thesis Waco and Strathalbyn soils), this maximum value occurs at a higher water content (between the plastic and liquid limits).

Since tillage involves some remoulding and disturbance of the soil, it is suggested that allowing a tilled thixotropic soil to rest for several days before any other operations are performed can increase the strength of the soil aggregates which have been disturbed by tillage. Due to crack formation (caused by wetting and drying) the tensile strength of clods or aggregates in the top (0 - 5 cm) layer of a tilled soil decreases with time after tillage. The shear strength or penetration resistance, on the other hand, might not be influenced by these cracks (see section 5.1), and it might even increase with time after tillage. For clods or aggregates in the deeper layer, since soil water content fluctuations, at least in the first few days after tillage, are negligible (section 6.1), in addition to shear strength increase, there might be an increase in tensile strength. With these strength increases, it can be expected that allowing a tilled thixotropic soil to rest for several days after the first implement pass results not only in a lower cost and energy in tilling the soil as discussed previously, but also in a reduction of compaction damage. This suggestion is supported by the result discussed in section 6.4 which shows that ageing aggregates disturbed by tillage can increase the resistance of beds of these aggregates to compression.

The effects of chemical soil conditioners on aggregate water stability have been widely reported. In this thesis, it has been shown that chemical conditioners also influence the strength of unsaturated soil (section 3.2). The addition of either phosphoric acid or calcium sulphate increase the soil sensitivity, which is defined as the ratio of the undisturbed soil strength to the remoulded strength. The application of phosphoric acid increases soil penetration resistance, but decreases the tensile strength of both remoulded and natural aggregates. Calcium sulphate, on the other hand, decreases the penetration resistance of remoulded soil, and increases the tensile strength of both remoulded and natural aggregates. Phosphoric acid addition decreases the resistance of beds of aggregates as a consequence of its effect in decreasing aggregate tensile strength. Likewise, since calcium sulphate increases the tensile strength of soil aggregates, the addition of this chemical has been found to increase the resistance of beds of these aggregates to compression. This finding is consistent with the work of Braunack and Dexter (1978) which showed that the resistance of beds of aggregates to compression increased with increasing tensile strength of the individual aggregates.

On the basis of these results, it is suggested that conditioners which decrease aggregate tensile strength (in this thesis, phosphoric acid) should not be used in a soil which already has aggregates of low tensile strength. Although such conditioners can increase aggregate water stability (e.g. Yeoh, 1979), but to a decrease in aggregate tensile strength, the soil could be more susceptible to compaction damage. Phosphoric acid (and any other conditioner which decrease aggregate tensile strength) would be more valuable if it is used in a hard strong soil. In this case, the double beneficial effects of phosphoric acid, that is an increase in aggregate water stability, and a decrease in aggregate tensile strength so that the soil can be broken more easily, can be expected. Phosphoric acid might also be useful in restoration of some soils which have been degraded by the formation of hard-pan layers.

Since calcium sulphate increases aggregate tensile strength, it is suggested that this chemical (and any other chemical which increase aggregate tensile strength) should be used in soil with aggregates of low initial tensile strength. The double beneficial effects of calcium sulphate, that is to increase aggregate water stability, and to increase aggregate tensile strength with a consequence of increasing the resistance of the soil to compression can then be attained.

The measurement of soil friability developed in section 5.2 has been found to be very useful for the prediction of the soil water content which gives maximum soil crumbling when the soil is tilled. This approach is based on a brittle fracture theory for soil aggregates developed by Braunack *et al.* (1979). The friability is measured by the value of the parameter k of equation

$$\log_e \sigma_T = K - k \log_e V \qquad (7.1)$$

where σ_T, and V are the tensile strength and the volume of individual aggregates respectively, and K and k are adjustable parameters. The value of k ranges from $k < 0.05$ (which is considered to be not friable) to $k > 0.40$ (which is considered to be mechanically unstable).

The Urrbrae and Strathalbyn soils, and probably most other soils, are most friable at water contents corresponding to a matric water potential of -100 kPa (W = 18.1% for the Urrbrae soil and W = 16.3 for the Strathalbyn soil). At this water content the Urrbrae soil has a k value of 0.28, and the Strathalbyn soil has a k value of 0.22. The optimum water content for tillage predicted by this theory (which is slightly below the plastic limit) is in good agreement with that found in previous tillage experiments (Lyles and Woodruff, 1962; Bushan and Ghildyal, 1972; Ojeniyi and Dexter, 1979a).

With this theory it is possible to explain why this optimum water content occurs. It is widely known that when tillage is done in very wet soils, it cannot produce a good tilth, and may even destroy the previously existing aggregates. Likewise when tillage is performed in a dry soil, excessively large clods are produced instead of small stable aggregates. As shown in section 5.2, at these water contents the Urrbrae and Strathalbyn soils, and probably most other soils, have a small k value, and are therefore not friable. Under these conditions, the strength of any small soil aggregates does not differ much from that of the soil mass itself. Thus, when this soil is tilled, it cannot break up into mechanically stable soil aggregates, but it will break up into individual particles or dust (if the tensile strength is very low) or turn up into large clods (if the tensile strength is very high). Thus, at these water contents, tillage is not able to make use of the pre-existing planes of weakness.

This approach could be useful in the study of the effects of soil management practices, such as the application of soil conditioners, stubble management etc., on soil physical properties, because friability is almost synonimous with the quality of the physical condition of an unsaturated soil. It has been shown (section 3.2) that the application of chemical conditioners not only influences soil strength, but also soil friability as measured by the parameter k of equation (7.1). Wetting and drying and freezing and thawing cycles have also been shown to influence the friability, k. It is therefore suggested that in a soil of low strength, soil management practice should be directed to increase soil strength, and at the same time should also increase the friability of the soil. Thus to obtain maximum benefit, the application of calcium sulphate (since it decreases soil friability as shown in section 3.2) should be combined with other management practices which can increase soil friability, such as by increasing the amplitude of wetting and drying etc. For phosphoric acid, it seems that when it is used in soil of high tensile strength there is no problem, because besides decreasing tensile strength, it is also able to increase soil friability.

The measurement of soil friability may also prove to be useful to explain other soil mechanical phenomena. As discussed in section 2.1.4, Bushan and Ghildyal (1971; 1972) found that the mean weight diameter (MWD) of clods produced by tillage increased with increasing radius of curvature of the implement. This is not surprising. Implements of greater radius (i.e. less curved implements) probably produce smaller compressive stresses in the soil. Such compressive stresses can give rise to clod or aggregate tensile failure. The size of the resulting fragments depends on the value of the soil friability, k.

7.3 Suggestions for further work

It has been shown (section 6.2) that under South Australian conditions, the increase in the amplitude of wetting and drying of a soil tilled with one implement pass can result in greater clod fragmentation in the second implement pass. In another study, Utomo and Dexter (1981c) found that this practice did not result in a significant change in the fragmentation of soils of the Coombe and Wicken soil series of England.

The reason for this difference in behaviour is not yet understood. Clearly, the appropriate amplitudes of wetting and drying for internal micro-cracking are not attained in these soils. This might be a consequence of the climatic conditions prevailing during the experiment and/or a consequence of the values of certain key physical properties of the soils resulting, perhaps, from their mineralogy and chemistry. Further experiments to investigate these factors would be very useful to explain this phenomenon.

The increase in soil strength after remoulding or disturbance (section 3.1) can be taken into account in soil management practice to reduce compaction damage caused by the weight of agricultural implements. It has been suggested that this process might also influence seed germination and crop growth. To test this suggestion, further experiments into factors such as the effects of matric water potential changes which accompany thixotropic hardening on plant water availability, and the effects of increasing soil strength and changing pore size distribution on water and plant nutrient movement, are required. Investigations into the optimum soil structures required for crop growth, such as suggested by Koenigs (1961) for rice, could also be related to the thixotropy phenomenon.

As discussed in section 3.2, the application rate of calcium sulphate in this work might be considered too high from the agricultural point of view. An investigation to study the minimum application rate which can increase soil strength, or to obtain other chemical conditioners which could economically increase soil strength would be very useful for managing soils of low strength.

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APPENDIX

Cumulative errors relating from summing differences between consecutive sub-samples of a population.

Equation (6.5) gives the sum of the differences between consecutive measurements of soil water content. An error term arises because these water content measurements are not exact, but are the means of small sub-samples from a supposedly random population with mean μ and standard deviation σ.

If there are (n + 1) times of measurement, and if at each time of measurement k replicate measurements are made, then the (n + 1) mean values from these k replicates can be labelled

$$\bar{x}_i \ , \ i = 0, \ \ldots \ , n.$$

The limiting distribution of $\sqrt{k}\ (\bar{x}_i - \mu)/\sigma$ is normal, n(0,1) by the Central Limit Theorem. Hence we can take the $\bar{x}_i$ as being normally distributed, $n(\mu, \sigma/\sqrt{k})$.

A sequence of variables y_i can be formed:

$$y_i = |\bar{x}_i - \bar{x}_{i-1}|, \quad i = 1, \ \ldots \ , n \tag{A1}$$

It will be noticed that the ΔW_i of equation (6.5) are related to the y_i by

$$\Delta W_i = y_{2i} + y_{2i-1}, \ i = 1, \ \ldots \ , j \tag{A2}$$

Now, it can be shown that the y_i are not independent. However, they can be divided into two sequences such that

$$\sum_{i=1}^{n} = (y_1 + y_3 + y_5 + \ldots\ldots) + (y_2 + y_4 + y_6 + \ldots\ldots)$$

$$= S_1 + S_2, \tag{A3}$$

and these two sequences do contain independent variables. Each of these sequences can be independently analysed, and, by the Central Limit Theorem:

$$\frac{S_1 - \frac{1}{2}n\mu'}{\sigma'\sqrt{n/2}} \sim n(0,1) \quad ; \quad \frac{S_2 - \frac{1}{2}n\mu'}{\sigma'\sqrt{n/2}} \sim n(0,1) \qquad \text{(A4)}$$

Here, the μ' and σ' are the means and standard deviations of the random variable Y, of which the measured values are y_i. Thus a graph of $\sum_{i=1}^{n} y_i$ against n will be a straight line with a slope μ'.

The value

$$\mu' = E(|\bar{x}_i - \bar{x}_{i-1}|)$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |\bar{x}_i - \bar{x}_{i-1}| \left(\frac{\sqrt{k}}{\sigma\sqrt{2\pi}} e^{-(\bar{x}_i - \mu)^2 k/2\sigma^2}\right)$$

$$\left(\frac{\sqrt{k}}{\sigma\sqrt{2\pi}} e^{-(\bar{x}_{i-1} - \mu)^2 k/2\sigma^2}\right) d\bar{x}_i d\bar{x}_{i-1} \qquad \text{(A5)}$$

Putting $x = \frac{(\bar{x}_i - \mu)\sqrt{k}}{\sigma}$ and $y = \frac{(\bar{x}_{i-1} - \mu)\sqrt{k}}{\sigma}$ gives

$$\mu' = \frac{\sigma}{2\pi\sqrt{k}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |x - y| \, e^{-(x^2 + y^2)/2} \, dxdy \qquad \text{(A6)}$$

and changing to polar coordinates gives

$$\mu' = \frac{\sigma}{2\pi\sqrt{k}} \int_{0}^{2\pi} |\cos\theta - \sin\theta| \, d\theta . \int_{0}^{\infty} r^2 e^{-r^2/2}$$

$$\mu' = 2\sigma/\sqrt{\pi k} \qquad \text{(A7)}$$

Thus values of $\Sigma\Delta W_j$, as defined in equations (6.5) and (A2) contain, in addition to "genuine" water content changes, error terms equal to $4j\sigma/\sqrt{\pi k}$ which result from taking finite samples of size k from a normal population.