Effect of the size and stability of soil aggregates on germination, emergence, establishment and subsequent growth of wheat.

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SUMMARY

The effects of soil structure on the growth of wheat were examined in field and glasshouse studies.

Field studies

A field experiment was conducted on red-brown earth (Urrbrae loam) to investigate the influence of the size and stability of soil aggregates on germination, emergence establishment and growth of wheat. Stratified seed-beds, 8 cm deep were prepared in small plots (50 x 50 cm) from aggregates obtained by dry sieving the soil. The seed-beds comprised two layers each of 4 cm depth and the aggregate sizes were 2 - 4 mm/< 2 mm, 4 - 8 mm/2 mm and 4 - 8 mm/2 - 4 mm. Unstratified seed-beds 8 cm deep were prepared from unsorted aggregates < 8 mm diameter. Half the plots were prepared from aggregates containing 0.2 % poly (vinyl alcohol), P.V.A. to stabilise the structure. One hundred wheat grains were sown at 4 cm depth in each plot.

Germination of the wheat was satisfactory (96.9 ± 0.28) and was similar in all the plots. The number of plants which finally emerged and become established was not affected by aggregate size or P.V.A. treatments, but the rates of emergence of plants in seed-beds made of 2 - 4 mm/< 2 mm aggregates and of unsorted aggregates < 8 mm, were higher than in other seed-beds (4 - 8 mm/2 - 4 mm and 4 - 8 mm/< 2 mm). The dry weight of plants at tillering and straw and grain yields at maturity were lower for plants grown in seed-beds 4 - 8 mm/2 - 4 mm and 4 - 8 mm/< 2 mm than for plants grown in seed-beds 2 - 4 mm/< 2 mm and unsorted aggregates < 8 mm. Treatment of the soil with P.V.A. decreased dry matter production and grain yield although the decreases were not always significant at $P < 0.05$. The plots where greater dry matter and grain yield was obtained were those which gave the earliest plant emergence and where the plants had the highest concentrations and total content of nitrogen.

Geometrical macro-structure of the surface layer of the soil was measured at sowing, germination, emergence and tillering, on sections cut through blocks of resin impregnated soil. Total macroporosity and mean pore size at 0.5 cm depth decreased during the eight weeks following sowing of the wheat particularly where the soil had not been treated with P.V.A.. The lowest macroporosity occurred at emergence, 3 weeks after sowing. Total porosity and mean pore size were consistently higher in the surface soil of seed-beds with aggregates initially 4 - 8 mm in diameter than in seed-beds 2 - 4 mm diameter aggregates. Soil treated with P.V.A. had greater porosity and greater mean pore size than untreated soil at all times of measurements.

Measurements made at 4 cm and 8 cm depth in the soil from sowing to emergence of the wheat showed that soil temperature was similar in all the plots. Soil water potential at 4 cm depth was higher (less negative) in plots made of aggregates 2 - 4 mm/2 mm than in plots made of aggregates 4 - 8 mm/2 mm and 4 - 8 mm/2 - 4 mm diameter. Meteorological factors had a greater influence on temperature and water in the soil than did the treatments. Regression analysis showed that soil temperature was most closely related to the relative humidity of the air and to rainfall which soil water potential was most highly correlated with water pressure deficit.

Surface crusting and seedling emergence

The effect of surface crusting of the soil on emergence of wheat was investigated in a glasshouse experiment. Seed-beds consisting of 8 cm depth unsorted (< 8 mm) soil overlain by 4 cm of < 2, 2 - 4 or 4 - 8 mm diameter aggregates were prepared. Wheat was sown at 4 cm depth in air dry soil and the water content of the soil was then adjusted to

20 % by weight by spraying 25 mm of 'rain' onto the soil surface. Different soil water regimes were produced by covering the soil in two sets of pots with a plastic mulch 0 and 3 days after the pots were watered, while the soil in the third set of pots was left uncovered. As expected, the strength of the soil as measured by penetrometer resistance at the time of emergence of wheat increased with decreasing water content of the soil. The strength of the crust which formed from small aggregates (< 2 mm) was significantly greater than those formed from the larger aggregates. In some instances, treatment of the soil with poly (vinyl alcohol) significantly lowered the strength of the crust. In general emergence of the wheat decreased with decreasing soil water content and with increasing crust strength. Emergence was markedly decreased or no emergence occurred as crust strength increased from 90 to 341 kPa.

Production and movement of mineral nitrogen in beds of different sized soil aggregates

Aggregates < 2, 2 - 4 and 4 - 8 mm diameter were subjected to aerobic incubation at 12 or 24 % water content for up to six weeks under two fluctuating temperature regimes *viz* alternating 12 h periods at 5 and 10°C or 12 and 24°C. Net mineralisation of nitrogen was higher at 24 % water content and 12/24°C than at lower water content and lower temperature regime. However the amounts of ammonium and nitrate produced during the six week incubation period were similar in aggregates of all sizes, and were not affected by treatment of the soil with P.V.A..

Stratified beds of aggregates (8 cm deep) underlain by undisturbed cores of subsoil (20 cm deep) were set up in leaching tubes. The beds were constructed as described for the field experiment described above and ammonium sulphate was added to the lower layer of aggregates in each tube. The columns were leached with rain water at various rates and frequencies of application and the volume and mineral nitrogen content

of the leachates were determined at weekly intervals for four weeks. Treatment of the aggregates with P.V.A. permitted greater percolation of water and greater loss of mineral nitrogen from the soil columns, particularly where the surface layer of the bed comprised coarse aggregates. The size of the aggregates had little effect on the total amount of ammonium and nitrate leached where the beds were not treated with P.V.A.

Under the conditions in which the field experiment was carried out aggregate size had more effect on plant emergence, establishment and growth of wheat than stratification of aggregates. Aggregate size and aggregate stability affected nitrogen uptake by the plants. Aggregate size and aggregate stability may have had an effect on leaching of nitrogen in the field.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. This thesis contains no material published previously or written by any other person, except where due reference is made in the text of the thesis.

May 1982. Smail Anser

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SECTION 1. INTRODUCTION

Soil structure as described by the shape, the size distribution and stability of aggregates, has an overriding influence on germination and emergence of plants in so far as it controls the environment (i.e. the temperature, water content and aeration) of the soil in which seeds germinate and roots develop. Because the early growth of plants can substantially affect the later performance of the crop, including the final yield, it is important that soil conditions which affect germination, emergence and establishment should be fully considered. Unfortunately, in many studies of the effects of seed-bed preparation on crop production, this has not been so. The quantitative description of seed-beds has received inadequate attention.

According to Taylor (1974), a good seed-bed should consist of soil aggregates of appropriate size to ensure (1) an accurate seed placement both in depth and spacing interval (2) adequate contact between seed and soil to allow a rapid and uniform germination and (3) good root-soil contact to permit extraction of water and nutrients. In semi-arid areas where water shortage may limit crop production, the seed-bed should also minimise loss of water by evaporation. The best range of aggregate sizes to fulfil these requirements is clearly going to vary with such factors as seed-size, stability of aggregates and climatic conditions, which may account for the different ranges of aggregate size found to be the most desirable for plant growth in different situations. However researchers generally agree that medium sized aggregates (1 - 8 mm diameter) are superior to smaller or larger aggregates for establishment and growth of plants. The larger range of aggregates may be more desirable where the structure is unstable as it takes longer with large aggregates for the undesirable consequences of unstability on other physical properties of the soil (e.g. slow water infiltration, formation of surface crusts) to become effective.

Soil structure is important not only with respect to soil physical properties but also to chemical properties and microbiological activity. For example, the rates of nitrogen transformations in the soil, the availability of nitrogen to plants and consequently plant growth are very much influenced by the way which the size and stability of the aggregates control water supply and aeration (Wiersum 1962; Hagin 1952).

Most studies specifically designed to test the effect of aggregate size on emergence, establishment and yield of various crops have been performed using seed-beds of sieved aggregates with narrow size-range distributions. This method is preferred because seed-beds obtained in this way can be reproduced in time and in space and the results of different experiments compared. Seed-beds prepared by tillage have a wide range of aggregate sizes the extent of which varies with many factors including soil texture, water content, the type of implement used and the timing of the tillage operations. Consequently such seed-beds are difficult to reproduce and any conclusions drawn from the results of experiments may not be widely applicable. Generally studies of the effects of different sized aggregates on crop growth have employed uniform layers of aggregates (Edwards 1957a; Russell 1961; Hoyle *et al.* 1972; Taylor 1974; Braunack 1979). In practice, however the distribution of aggregates is not uniform throughout the cultivated layer of soil. Tillage operations more or less segregate the aggregates and produce seed-beds in which large aggregates predominate towards the surface and small aggregates predominate in the lower layers (Kouvenhoven and Terpstra 1970, 1977). Segregation of aggregates can significantly influence the properties of the seed-bed. For example, the amount of water lost by evaporation may be less than that for soil in which the various sized aggregates are uniformly distributed throughout the cultivated layer (Johnson and Buchele 1961; Hillel and Hadas 1972; Hadas 1975). It is pertinent therefore to examine in some detail the effect which the segregation of aggregates can have on plant growth.

This thesis reports the results of a field investigation on the effects of the size and stability of soil aggregates on the growth of wheat. The aggregates were obtained by sieving, their stability varied by treatment with poly (vinyl alcohol) and layers of different sized aggregates were used to produce stratified seed-beds. In particular the investigation was designed:

1. to obtain a quantitative description of the structure of seed-beds and how the structure changed with time,
2. to examine how water potential and temperature in the seed-beds were affected by aggregate size, aggregate stability and meteorological factors, and
3. to examine the effects of aggregate size and aggregate stability on germination, establishment and yield of wheat.

Subsequent experiments conducted in a glass house examined in more detail:

4. the relationship between the emergence of wheat and crust strength as affected by aggregate size, stability and water content, and
5. the relationship between soil structure and the net mineralisation and leaching of nitrogen.

SECTION 2. LITERATURE REVIEW

2.1 GENERAL

Soil structure is caused mainly by physical forces such as those induced by changes in water content, freezing and thawing, by the effects of root growth and the activity of earthworms (Pizer 1961; Marshall 1962; Batey and Davies 1971). These factors cause soil particles to join together or break down into units, with their size and shape depending on soil type and (under agricultural systems) on the type of management to which the soil is subjected.

Cultivation plays an important role in modifying topsoil structure by loosening or consolidating the soil and by breaking larger clods into smaller aggregates suitable for seed-beds. One of the objectives of soil cultivation is to create a soil environment suitable for seed germination, plant emergence and subsequent growth. Soil environmental factors which most affect growth are water retention, aeration, the thermal properties of the soil, nutrient availability and soil strength (Marshall 1962; Baver et al. 1972; Hillel 1972; Taylor 1974). A fine compact structure may be required to ensure good soil-root contact and moist conditions for seeds during germination, but an open structure may be better for root activity. Tillage must be aimed at achieving a compromise between these objectives. Different soil types and climatic conditions require different methods of soil and water management for most effective plant growth. In semi-arid areas, tillage should be performed in such a way as to encourage water infiltration, to minimize water loss through evaporation, to avoid the formation of soil crusts and to increase soil fertility by providing conditions favourable to the mineralisation of organic matter (Marshall 1962).

Two important factors influencing the structure and surface conditions produced by tillage of a particular soil are the water content of the soil at the time of tillage and the type of implement used (Lyles and Woodruff 1962). Aggregate size is the soil property most directly altered by tillage. The extent of the alteration is dependent upon the soil condition at the time of the tillage as well as the intensity of the operations. Siddoway (1963) and Amemiya (1965) found that each tillage implement exhibited a characteristic size distribution. For example, the mouldboard plough was found to produce a predominance of intermediate sized aggregates (6 to 19 mm diameter) while a sweep plough produced the largest clods and the smallest aggregates. A good seed-bed is considered to have a profile with a relatively high proportion of small aggregates in the vicinity of the seed to promote contact between seed and soil, and a coarser mixture at the surface to prevent dissipation of the soil by wind and water erosion and to reduce the growth of weeds. Such a profile is the result of the sorting and mixing action of the tined implements such as harrows and cultivators (Kouwenhoven and Terpstra 1970). Different aggregate sizes produced by tillage can have different physical properties such as erodibility and stability (Lyles and Woodruff 1962; Siddoway 1963) and chemical properties such as clay and organic matter content (Nijhawan and Dhingra 1947; Tabatabai and Hanway 1968b). On this basis it seems appropriate to use soil aggregate size as a parameter to study the relationship between soil structure and processes and properties such as movement and retention of water, water evaporation, soil strength, aeration and to try to define desirable conditions for seed germination, plant emergence and growth and then to try to create these conditions with tillage.

2.2 PROPERTIES AND BEHAVIOUR OF DIFFERENT SIZED AGGREGATES

The most important chemical properties of soil aggregates are their clay and organic matter content. These properties are closely related to many other chemical properties of the soil such as carbon content, cation exchange capacity, exchangeable H^+ and Ca^{++} (Alderfer and Merckle 1942; Wittmuss and Mazurak 1958; Tabatabai and Hanway 1968b) and to physical properties such as bulk density, aggregate stability, water and wind erodibility (Metzger and Hide 1938; Alderfer and Merckle 1942; Tabatabai and Hanway 1968b; Moldenhauer and Koswara 1968).

2.2.1 Organic matter content

Many workers have measured the organic matter content of different sized aggregates. Metzger and Hide (1938) found that organic carbon in Derby silt loam of Kansas generally increased with increasing size of aggregates (the sizes were not given). A similar observation was made by Alderfer and Merckle (1942). They found that the organic matter content of aggregates from Pennsylvannia soils under bluegrass increased from 3.6 to 4.3 percent as the size of aggregates increased from (1 - 0.2) to > 2 mm diameter. Some other workers have shown that organic matter or organic carbon content of soil aggregates was inversely related to the size of aggregates. Among the latter workers, Garey (1954) observed that organic carbon content of aggregates from various soils was greater in aggregates >0.42mm than in aggregates 0.42 - 0.15 mm diameter. (The decrease was from 5.1 to 3.5 for Houston clay soil, 3.6 to 1.9 for Sharkey clay soil and from 3.2 to 1.4 % for Crowley silt loam.) Management of a soil can influence the organic matter content of the soil (Turcheneck and Oades 1978). Organic matter is lost from soils which are cultivated frequently, especially if fallow is included in the rotation or crop residues are removed (Ridley and Hedlin 1968; Martel and Paul 1974; Juo and Lal 1975).

Craswell *et al.* (1970) found no difference in organic matter content of different sized aggregates in tilled soils, but a higher organic matter content was found in aggregates of 1.0 - 0.5 mm than in smaller or larger aggregates from soil under permanent grass. Tabatabai and Hanway (1968b) analysed aggregates of 9.0, 5 - 9, 3 - 5, 2 - 3, 1 - 2, 0.5 - 1 and < 0.5 mm diameter size range from soil under grass and concluded that organic carbon increased with decreasing aggregate size in both surface soil and sub-soil. Organic matter content of soil aggregates was found to be related to the type of crop grown because different crops produce different phytomass (Clement 1961). Metzger and Hide (1938) found that where maize and oats were grown, organic matter content increased with increasing size of aggregates. This increase was 1.64 to 1.87 and 1.62 to 1.82 % of organic matter respectively.

2.2.2 Clay content

The physical and chemical properties of different sized aggregates were also found to be influenced by the clay content of these aggregates (Alderfer and Merckle 1942; Garey 1954; Tabatabai and Hanway 1968b, Gumbs and Warketin 1976). The stable aggregation of some soils was found to be related to percentage of clay content < .002 mm (Alderfer and Merckle 1942; Garey 1954). Baver and Harper (1935) have shown that failure of certain desert soils to form aggregates larger than 0.05 mm is associated with the low clay and organic matter content of such soils. Cation exchange capacity was found to be 11.5 m.e./100 g in Crowley silt loam soils which contained 15.6 % clay and 36.6 m.e./100 in Sharkey clay soil which contained 63.2 % clay (Garey 1954). Aggregate size was found to be related to the clay content of soils, but the correlations are not always good (Tabatabai and Hanway 1968b). Alderfer and Merckle (1942) found that in a cultivated soil, clay content increased with increasing size of aggregates from (1 - 0.2) to > 2 mm diameter. The same trend was found for soil under grass. However Garey (1954) found that small aggregates, 0.15 - 0.42 mm diameter, tended to contain a larger per centage of clay than larger aggregates or the whole soil. Tabatabai and Hanway (1968b) found that there was little difference of clay content in aggregates > 9.0 to 1 - 2 mm size range. These contradictory results reported by different authors might be explained by the fact that some researchers used aggregates obtained from cultivated (and hence mixed) soil as opposed to soil which had not been cultivated. In the latter case, greater differences in the properties of aggregates of different size might be expected.

2.2.3 Bulk density and porosity

Many workers have reported a relationship between bulk density and aggregate size. Tabatabai and Hanway (1968b) observed that bulk density decreased as the size of aggregates decreased from > 9.0 to 0.5 - 1 mm diameter size range. They also found that for each increase of 1 per cent in organic carbon content, the bulk density of aggregates > 9.0, 5 - 9, 3 - 5, 2 - 3, 1 - 2, 0.5 - 1 mm diameter decreased by 0.25 g cm^{-3}. Other workers have found that bulk density increased with decreasing the size of aggregates. For example, Wittmuss and Mazurak (1958) found that as the size of aggregates decreased from 4.76 to 0.18 mm diameter, their bulk density increased. The confliciting observations may be a consequence of the use of different soils, different aggregate size ranges and whether or not the composition of the aggregates (e.g. organic carbon) varies with size. Currie (1965) pointed out that the inverse relationship between dry bulk density and aggregate size can be explained by the fact that with decreasing size, the percentage of total pores exposed at the aggregate surface increases and the porosity decreases. Each decrease in aggregate size means that the pore fraction of that size in the aggregate is eliminated.

2.2.4 Aggregate stability

It has been established that the inherent properties of the soil such as texture, organic matter and calcium carbonate content as well as environmental effects of weather and climate can affect the stability of aggregates (Chepil 1953, 1954, 1958; Mazurak and Mosher 1970; Benoit 1973). On cultivated land, tillage, cropping systems and other management practices exert additional influences on aggregation (Mazurak *et al.* 1954; Chepil 1955; Blavia *et al.* 1971). Several chemical properties have been related to the water stability of aggregates of different size. Alderfer and Merckle (1942) observed that stability of aggregates > 2, 2 - 1 and 1 - 0.2 mm diameter was closely related to the organic matter content and clay content of each aggregate size range. Similar results were obtained by Wittmuss and Mazurak (1958), who found that as the diameter of aggregates decreased from 4.76 to 0.18 mm their water stability increased. There was highly significant correlation between stability of the same aggregate size range and exchangeable Ca^{++} and H^{+}, and available phosphorus. The authors also reported that one cycle of wetting and drying of the soil had different effects on the stability of aggregates of different diameter. The stability of aggregates 2.38 - 0.74 mm diameter was greater than that of aggregates 4.76 - 2.38 mm diameter after one cycle of wetting and drying.

In cold climates, the effects of freezing and thawing on aggregates can be important. However very little work has been done on the effect of freezing and thawing on different aggregate sizes. Benoit (1973) reported that the percentage of water-stable aggregates < 0.8 mm diameter increased by a factor of 1.26 from initial values after freezing and thawing at -5 kPa water potential level and -4°C freezing temperature.

The effect of cropping and management practices on aggregate stability (and differences in stability with size) can be attributed largely to the effects of organic matter content. Macro-aggregates in cultivated soils are less stable than macro-aggregates in corresponding virgin soil or soil under old pasture (Low 1954; Juo and Lal 1975). The amount of stable aggregates (> 2 mm diameter) in an old arable red-brown earth to a depth of 50 mm was about 2 per cent of that in the corresponding virgin soil (Greacen 1958). Siddoway (1963) found that the proportion of stable aggregates was greater when a straw residue was returned to the soil than when it was burned or partially removed. In young pastures most of the increase in aggregation occurs in the top layers of the soil because organic materials accumulate at the surface (Clement and Williams 1961).

Lyles and Woodruff (1962) found different tillage implements produced aggregates of different stability because different implements produced different aggregate size distributions. The decreasing order of their effectiveness in producing stable aggregates was mouldboard plough, one-way disc and sweep plough, when tillage was done at the soil water content common to spring tillage.

2.2.5 Erosion and surface crusting

The two main agencies which cause soil erosion are rainfall and wind. The literature on erosion is very extensive but comparatively few studies have been concerned specifically with the relationship between the size of aggregates and soil erosion and surface crusting.

(a) Rainfall

Erosion by rainfall is function of the intensity and distribution of the rainfall and the diameter of the rain drops and their energy (Ellison and Slater 1945; Moldenhauer and Kemper 1969). Soil characteristics that are important include soil texture, and the size and stability of the surface aggregates (Ellison and Slater 1945; Chepil 1953; Rai *et al.* 1954; Alderman 1956; Rose 1961; Moldenhauer *et al.* 1967, 1969; Mazurak and Mosher 1970; Blavia *et al.* 1971).

The erosion of soil aggregates by rainfall is accomplished by removal of material by the shearing action of raindrops. The material detached is carried into the underlayering pores by infiltrating water (Cary and Evans 1974). The fine material thus washed in decreases the porosity of the soil. If porosity is decreased to the point where water infiltration rate is exceeded by rainfall rate, surface run-off occurs. Surface crusts commonly about 5 mm thick may be formed when the soil dries. Moldenhauer and Kemper (1967) found that when water was applied to aggregates 8 - 20 mm diameter, the infiltration decreased from 200 to 0.3 cm h^{-1} as the cumulative energy of water was increased from 0.025 to 0.2 J cm^{-2}. When water was applied with the same energy to aggregates 4.7 - 8.0 mm diameter, the infiltration decreased from 10 to 0.2 cm h^{-1} (Moldenhauer and Kemper 1969). They attributed the decrease in water intake to the reduction of surface pores following the breakdown of aggregates. Mazurak and Mosher (1970) found that the amount of particles detached from aggregates 9.25 to < 2.1 mm diameter was linearly related to the rainfall intensity. Similar conclusions were reached by Rai *et al.* (1954).

The stability of the aggregates clearly influences their erodibility by water. For example, Mazurak and Mosher (1970) found that when aggregates 9.25 - 4.76 mm diameter were treated with "Krilium" (a hydrolysed polyacrilonitrile, which has been used as a soil stabilizer), the weight of soil particles detached was 5 mg cm^{-3} of water applied, but when aggregates of the same size range were untreated, the weight of soil particles detached was 76 mg cm^{-3} of water applied.

Over the past few years, a number of attempts have been made to stabilise soil surface aggregates, to reduce the crusting tendency of soils and to encourage formation of a low-strength crust by the use of crop rotations, residue management and chemical additives. The effectiveness of various chemicals in stabilizing soil aggregates depends on the soil types to which they are applied, and it may be measured in terms of the energy required to initiate run-off compared to the energy required to initiate run-off on untreated aggregates (Mazurak and Mosher 1970; Blavia *et al.* 1971). Poly (vinyl alcohol), hereafter referred to as P.V.A., has been widely used to prevent soil crust formation (Carr and Greenland 1975). Page (1979) observed a big decrease in the crust strength of soil to which P.V.A. had been applied. The decrease was directly related to the rates of P.V.A. applied up to 54 kg ha^{-1}, but increases above this rate had no further effect on crust strength. Stefanson (1973) showed that rainfall acceptance of treated soil improved with increasing molecular weight of the P.V.A. This is in agreement with the results of Carr and Greenland (1972) who found that aggregate stability and water infiltration increased as molecular weight increased. Comparatively little work had been done on the effectiveness of various soil conditioners in stabilizing aggregates of different size. Blavia *et al.* (1971) determined that of all substances tested, P.V.A. and Vinyl acetate-maleic acid were the most effective in stabilising soil aggregates. They found that when these chemicals were applied, larger aggregates (4.2 mm) were less stable than smaller aggregates (2.97 mm). But aggregates < 2.10 mm did not respond well to treatments with these chemicals.

(b) Wind erosion

Dry soil fractions transported by wind are generally smaller than 0.84 mm diameter (Chepil and Woodruff 1963). Large aggregates are less easily removed because of their weight and also because they provide a rough surface which decreases the velocity of the turbulent wind above it (Chepil 1963). The order of susceptibility of different soil structural units in the dry state to wind erosion is (from lowest to highest) (1) water stable aggregates (2) clods (3) surface crusts and (4) fine materials (Chepil 1963; Chepil and Woodruff 1963).

2.3 ENVIRONMENTAL CONDITIONS IN SEED-BEDS

The three main soil environmental factors which are influenced by soil structure are aeration, water content, and temperature. The size distribution of aggregates in seed-beds has been observed to affect the capacity of the soil to retain and transmit air, water and heat (Holmes *et al.* 1960; Tamboli *et al.* 1964; Danielson 1972).

2.3.1 Aeration

Two classes of pores can be distinguished in aggregated soil, the larger inter-aggregate pores which are important in drainage and aeration, and the much smaller intra-aggregate pores which are important for holding water available to plants (Gumbs and Warketin 1976).

(a) Inter-aggregate porosity

It is generally agreed that gaseous exchange between the soil and the atmosphere occurs predominantly through diffusion but convective transport may be important when aggregate diameters are greater than about 10 mm and pore dimensions become large enough to permit air circulation which enhances convective transport (Holmes *et al.* 1960).

Whatever the major mechanism of transport, inter-aggregate porosity is the main factor influencing the gaseous exchange controlling the availability of oxygen and removal of carbon dioxide from the soil (Hagin 1952; Doyle and Maclean 1958; Grable and Siemer 1968). Inter-aggregate porosity is influenced by the size distribution of aggregates in the soil (Tamboli 1961; Grable and Siemer 1968). The smaller aggregate size range desirable for satisfactory plant growth with respect to soil aeration and root penetration is set by the minimum inter-aggregate pore diameter which permits free drainage of water and air circulation. The larger aggregate size range is set by potential respiration of the soil and by the coefficient of diffusion for the aggregate themselves (Currie 1961). Total inter-aggregate porosity of soil was found by Grable and Siemer (1968) to decrease from 40 to 25 per cent when the size of aggregates in the soil was decreased from 3 - 6 to 0.5 - 1 mm size range, when water potential was -4.4 kPa. Doyle and Maclean (1958) determined that oxygen diffusion in aggregated soil was proportional to aggregate size between < 0.1 and 5 - 10 mm.

(b) Intra-aggregate aeration

The porosity characteristics of aggregates and their aeration is important in such processes as water retention, nutrient availability and root proliferation. Voorhees *et al.* (1966) found that the volume of air at a given water content increased from 50 to 60 per cent as the diameter of aggregates increased from 2.0 to 10 mm diameter. Currie (1961) developed an equation relating gas diffusion to the size of aggregates:

$$\varepsilon_1 \quad \frac{\ell}{\gamma t} = \frac{1}{r^2} \frac{\gamma}{\gamma r} (Dr^2 \frac{\partial \ell}{\partial r}) + S \quad \text{where}$$

ε_1 is the porosity of the aggregate

D the coefficient of diffusion of gas

r the diameter of the aggregate

ℓ the concentration of gas in the pores at time t

S is the strength of source for the diffusing gas within the aggregates.

Gradwell (1973) found that aggregates which contained less than 2 - 3 per cent by volume of air filled pores at water contents between field capacity and wilting point are likely to be impenetrable by gaseous oxygen. Anaerobic conditions could prevail in the centre of such aggregates if they have a diameter greater than 10 mm. The presence of aggregates of this size in the soil may be unfavourable for root growth. It has been suggested that seed-beds should contain aggregates which are predominantly smaller than 10 mm to avoid anaerobic conditions in the centres in the aggregates, but larger than 1 mm, as smaller aggregates may also cause anaerobic conditions to prevail in the soil (Hagin 1956).

2.3.2 Water

(a) Water retention

The size distribution of aggregates was found to affect the capacity of the soil to retain and transmit water (Amemiya 1965; Absol and Palta 1970; Gumbs and Warkentin 1976). Tamboli *et al.* (1964) observed that between potentials of -10 and -100 kPa, the water retained increased from 16.9 per cent to 25 per cent by weight as the size of aggregates increased from 0.5 to 9.5 mm diameter. Similar results were obtained by Amemiya (1965) who emphasised that it was the pore size distribution and not the total pore volume of aggregates which was responsible for variation in water retention by various sized aggregates at high potentials. According to Amemiya (1965), the differences in intra-aggregate porosity are chiefly responsible for the differences in water retention of different sized aggregates at high potentials. At low potentials, water is held by the adsorptive forces of aggregates. The effect of these forces is determined by the mechanical composition of the soil aggregates and the nature of the clay contained by the aggregates.

(b) Evaporation

Evaporation of soil water after wetting may be characterised by three stages (Lemon 1956). The first stage is controlled by external conditions and last as long as the soil profile can supply water to the surface at the rate sufficient to satisfy the evaporative potential. In the second stage, as the soil dries out, the evaporation is governed by the soil hydraulic properties. In the third stage the evaporation is very low but its rate is constant. Feodoroff and Rafi (1963) found that the rate of evaporation in the first stage and in the second stage is higher in aggregates 5 - 10 mm diameter than in aggregates < 1 mm diameter. But in the third stage no difference of evaporation was observed between various aggregate sizes. Hillel and Hadas (1972) found that under isothermal conditions aggregates 0.5 - 2 mm diameter size range had lower water loss through evaporation then larger or smaller aggregates. This is in agreement with results obtained by Holmes *et al.* (1960) who observed a minimum water loss through evaporation in beds of aggregates 2.5 mm diameter. Hillel and Hadas (1972) found that water losses by evaporation depends on the depth of the aggregated layer of soil. They determined that minimum evaporative loss occurred at intermediate depth of soil layer (3 - 6 cm).

(c) Water movement

Numerous workers have investigated the effects of aggregate size on water movement. Among them Hubbell (1947) found that the infiltration rate of water was higher with aggregates 1.2 - 2.4 mm than with aggregates 0.25 - 0.6. He also found that the capillary rise was increased when soil contained 15 per cent of aggregates 0.25 - 0.6 mm diameter or 45 - 75 per cent of aggregates 1.2 - 2.4 mm diameter. Amemiya (1965) investigated the influence of aggregate size on the unsaturated capillary conductivity of aggregate beds. He determined that when water content - water potential relations were unaffected by aggregate size, capillary conductivity was a function of volumetric water content. He found that at low soil water content, conductivity was not affected by aggregate size between 0.5 - 5 mm diameter, but at higher water content (> 25 per cent) capillary conductivity was higher for aggregates 0.5 - 1 mm diameter than for aggregates 1 - 5 mm diameter. Benoit (1973) found that unidirectional freezing and thawing decreased hydraulic conductivity of the soil. The amount of decrease was found to be directly related to initial aggregate size and indirectly related to freezing temperature.

2.3.3 Temperature

The temperature of the soil depends on the mineralogical composition of the soil and its water content, and in the size and distribution of the aggregates (De Vries 1963). However, little work has been done relating aggregate size distribution of the soil to its temperature. Holmes *et al.* (1960) found that the surface temperature of the soil was higher with aggregates of 2 - 4 mm than with larger or smaller aggregates. Bhushan *et al.* (1974) studied the influence of aggregate sizes in the range 4.12 - 12 mm diameter and concluded that seed-beds with larger aggregates attained maximum temperature 14 hours earlier than smaller aggregates. Hadas (1977) observed that the thermal conductivity of an aggregated soil decreased as the size of the aggregates increased and as the total and inter-aggregate porosities increased. The size range of aggregates studied in this case were < 0.25, 0.25 - 0.50, 0.5 - 1.00, and 1.0 - 2.00 mm diameter.

2.4 AGGREGATE SIZE AND PLANT GROWTH

In order to get a better understanding of the effects of soil physical conditions on plant growth, various workers have measured the effects of aggregate size distributions in the soil on plant growth (Hagin 1952; Doyle and Maclean 1958; Miller and Mazurak 1958; Phillips and Kirkham 1962; Jaggi *et al*. 1972; Taylor 1974; Braunack 1979). The effects of aggregate size distribution vary with plant species (Edwards 1957a, 1957b, 1958; Larson 1964) and with the stage of plant growth (Edwards 1957a, 1957b, 1958; Larson 1964; Taylor 1974; Braunack 1979).

2.4.1 Germination

Standard germination tests performed under nearly ideal conditions in the laboratory are quite inadequate to predict the ability of seeds to germinate in the field where temperature and aeration may be far from satisfactory and the optimum contact between seed and moist soil necessary to allow rapid and uniform germination may not be attained.

Few field studies have investigated the effects of aggregate size on germination *per se*. Grable and Siemer (1968) found that there was no difference in germination of maize seeds sown in soil aggregates 0.5, 0.5 - 1, 1 - 2, 2 - 3 and 3.6 mm diameter at water potentials of 0, -0.3, -1.8, -4.8 and -6.8 kPa. Jain and Agrawal (1970) found that germination of sugar cane seeds was better in aggregates 3.2 to 6.4 mm diameter than in larger or smaller aggregates. The low germination in smaller aggregates was attributed to poor aeration. In very wet soil with poor aeration, rotting of the seed may occur. Seed - soil contact is influenced by the size distribution of aggregates around the seed

(Larson 1964; Taylor 1974). A decreased surface contact between the seed and moist soil in coarsly aggregated soil, a low rate of transmission of water across the interface between the soil and seed are likely to be the cause of a lower germination in larger aggregates (Larson 1964; Jain and Agrawal 1970).

2.4.2 Emergence

The phase of emergence and subsequent seedling establishment is critical since it determines the density of the stand obtained. It influences the degree of weed infestation and consequently affects the yield. Seedling emergence may be limited by extremes of soil temperature, low water content, low oxygen content and mechanical impedance. All these factors are dependent on soil structure including aggregate size distribution. A number of investigators have attempted to relate aggregate size to plant emergence, but the majority of these investigators have not measured the effect of aggregate size on germination separately from the effect of aggregate size on emergence. This is unsatisfactory, as failure of a plant to emergence could be due to the failure of the seed to germinate or to the soil conditions being unfavourable for subsequent growth and emergence. Edwards (1957a) observed that seedlings of barley and oats emerged earlier from seed-beds made of aggregates 12.7 - 9.5 mm diameter. Total emergence was 10 % higher in finer seed-beds than in coarser ones. Johnson and Taylor (1960) found the highest rate of emergence when 30 % of the soil in the seed-bed was < 2.54 mm diameter. Later, watering under controlled conditions, Johnson and Buchele (1961) found that as aggregate size increased from 1.2 to 8.5 mm and compactive pressure (bulk density) decreased, the rate of soil drying increased and maize emergence decreased. A stratified soil composed of a compact layer 3.6 cm deep composed of aggregates 1.2 mm diameter covered with larger aggregates (the sizes of which was not given) was highly effective in decreasing drying rate and soil crusting, hence giving a better emergence. Hammerton (1961a) found that emergence of both sugar and fodder beet was fastest and higher in beds of aggregates < 1 mm diameter than in beds of 3 to 6 mm, 6 to 9 or a mixture of aggregate sizes < 13 mm. The higher and rapid seedling emergence was considered to be due to better water supply characteristics and to a lower mechanical impedance in the finer seed-beds compared to the coarser seed-beds. In a greenhouse pot experiment, Thow (1963) examined the effect of a 1.2 cm deep layer above the seed, of aggregates 0.74 - 6.13, 6.13 - 30.63 and 30.63 - 55.13 mm diameter, the soil below the seed being similar in all cases. He found that the rate of emergence and the ultimate number of oat seedlings which emerged was higher in pots containing small aggregates. These results agree with those obtained by Taylor (1974) who found that seed-beds made of aggregates < 2 mm gave the best emergence of maize and sorghum. However, Braunack (1979) found that the total number of wheat seedlings which emerged in the field was higher in seed-beds made of aggregates 2 - 4 mm diameter than in seed-beds made of aggregates 1 - 2 or < 2 mm diameter, while the rate of emergence was the highest in aggregates 1 - 2 mm diameter. The interaction of aggregate size and aggregate stability was found to affect emergence of cowpea plants. At 24 % soil water content, aggregate size and stability had little effect on emergence, but at 12 % soil water content aggregates stabilized by treatment with "Krilium 6" permitted more plants to emerge than did unstabilized aggregates (Slater and Rodriguez 1954). The breakdown of surface aggregates brought about by rainfall or irrigation leads to the reduction in the mean size of the structural units (aggregates) and can result in the formation of a crust (Arndt 1965a, 1965b). This crust can effect the infiltration of water in the soil, run off water and soil erosion (McIntyre 1955) and consequently plant emergence. Soil crust strength limiting plant emergence was found to be dependent on the water content of the soil (Hanks and Thorp 1957). This could explain in part the results found by Slater and Rodriguez (1954).

2.4.3 Dry matter production

Aggregate size influences plant growth and yield mainly through its effects on the availability of oxygen, water and nutrient supply when plants were grown in beds of aggregates (Doyle and Maclean 1958; Hammerton 1961b; Taylor 1974). Hagin (1952) reported that wheat plants grown in aggregates 1 mm diameter produced a higher dry matter yield than plants grown in aggregates 0.5 - 0.07 mm diameter. He suggested that the low yield of plants grown in fine aggregates was due to an insufficient supply of oxygen which diminished the ability of the roots to absorb nutrients. However, Edwards (1957b, 1958) found that oats and barley grown in aggregates < 1 mm diameter grew better in terms of number of tiller per plant, number of plants per plot, and total dry matter production per plot, than plants grown in aggregates 1 - 3 mm or larger. Grain yield of both oats and barley was also found to be higher in plants grown on seed-beds made of aggregates < 1 mm diameter. However Jaggi *et al.* (1972) found a higher wheat grain yield was obtained in plants grown in aggregates 1 - 2 mm diameter than in finer or coarser seed-beds. These results agree with those obtained by Braunack (1979). Edwards (1958) suggested that the differences in yield found by various workers for plants grown on seed-beds prepared from sieved aggregates was due to the differences in soil texture and aggregate stability. When aggregates, and in particular small aggregates, are unstable, they are easily broken down by rainfall or irrigation causing surface crusting which leads to a decrease in soil aeration and water infiltration. Surface crusting can adversly affect yield by reducing plant emergence.

The decrease in water infiltration may affect the water content of the soil to the extent that subsequent growth of plants is adversely affected. Final yield is not easily related to the condition of the seed-bed and its effects on plant establishment and early growth as a number of other factors operate during the (comparatively) long period between sowing and harvest. Some of these factors such as plant disease, insects attack on the plants are not related or only indirectly related to soil structure.

2.4.4 Root growth

Root growth may be affected by the way in which soil structure controls the water and air supply in the soil (Hagin 1956; Cornforth 1968). The size, shape and strength of aggregates controls root distribution in the soil. Cornforth (1968) found that root weight from smaller aggregates were significantly higher than from large aggregates. Soil strength and the strength of individual aggregates can affect the way the roots grow (Taylor and Ratliff 1969; Dexter 1978). Dexter (1978) has shown that an 'optimum' soil macro-structure exists for a maximum growth of roots of a given species. This optimum structure depends on the strength of soil aggregates. This strength determines whether roots grow through or around aggregates. When wheat plants were grown in a bed of aggregates 3.5 - 6.4 mm size range, the proportion of the length of wheat roots which pass through the aggregates was found to decrease from 0.69 to 0 as the strength of the bed of aggregates was increased from 1 to 5 MPa (Dexter 1978). Whether roots grow into or around aggregates can have a significant effect on accessibility of nutrients.

2.4.5 Nutrient availability and uptake

Root density and distribution in soil have a large influence on nutrient uptake particularly for relatively immobile nutrients such as phosphorus (Wiersum 1962; Cornforth 1962). Aggregate size can affect nutrient uptake by influencing availability as different aggregate sizes may have different physical and chemical properties (Tabatabai and Hanway 1968b). Aggregate size can also affect nutrient uptake by influencing soil physical conditions and consequently nutrient availability. Nitrogen for example, may be lost by erosion, denitrification, volatilization, leaching or two or more of these processes (Wetselaar 1961; Thomas 1970; Boswell and Anderson 1970; Vlek *et al.* 1981). Nutrient mobility in the soil is related to the soil physical and structural conditions as well as to the soil texture. Nitrogen movement and leaching for example, is closely related to water movement in the soil which is related to soil structure in particular pore size distribution and pore space volume (2.3.2). The efficiency of percolating water in causing leaching of nitrogen is dependent on soil porosity expressed as a percentage of total pore space drained between -7 and -5 kPa (Terry and McCants 1968, 1970). The distance that nitrogen is moved downward is a function of the quantity of water entering the soil and the type of soil (Thomas 1970). When the soil surface is prone to crusting and run-off is a problem, low intensity rainfall is more efficient in moving nitrogen down the soil profile, but when water run-off is low, high intensity rainfall is more efficient in leaching soil nitrogen (Thomas 1970). Bates and Tisdale (1957) found that, when factors such as water content of the soil at initiation of leaching, soil texture, surface evaporation and placement of salts in the soil are known, the movement of nitrogen can be predicted with some accuracy. They developed an equation relating soil porosity and the amount of water added to the quantity of nitrogen leached as follows:

$$Y = -12.93 + 64.66\ X_1 + 87\ X_2$$

where X_1 is the porosity index of the soil expressed as a percentage of total pore space drained between -4.9 and 0 kPa and X_2 = porosity index

X_1 x amount of mm of water added. Leaching of nitrogen can also be affected by the absence or presence of plants. Long and Huck (1980) found that maize root densities of 2 to 10 cm cm^{-3} prevented leaching of nitrogen applied to the soil at the rate of 200 and 500 kg ha^{-1} and only 2 - 3 % of nitrogen applied leached below 16.0 cm depth.

When no nitrogen fertilizers are added and in the absence of biological nitrogen fixation, soil nitrogen availability is dependent on the rate at which organic nitrogen can be converted to mineral nitrogen. This conversion is largely a microbial process which is to a great extent dependent on water content, temperature and oxygen in the soil. These three factors are largely controlled by the structure of the soil profile. Several workers have studied the effects of soil structure on the mineralisation of nitrogen. The main basis for interpretation of various results has been the effect of soil aeration on nitrification. Seifert (1964) found that the degree of nitrification and the nitrate level in the soil aggregates was in inverse proportion to the size of aggregates 5 - 4, 4 - 3, 3 - 2, 2 - 1, 1 - 0.75 and 0.75 - 0.5 mm size range. This may be due to the fact that aeration is poor in the centre of large aggregates (Greenwood and Goodman 1967). Waring and Bremner (1964) found that the amount of nitrogen mineralised by incubation of aggregates < 0.84 mm diameter was 24 to 124 percent greater than that of aggregates < 2 mm diameter. He stated that "some of the organic matter in soil aggregates is not susceptible to microbial decomposition until the aggregates are disrupted by grinding or other process that render the organic matter physically accessible to micro organisms". These results agree with those obtained by Craswell *et al.* (1970) who attributed the low nitrogen mineralisation in large aggregates to the fact that formation of macro-aggregates causes some soil organic matter to become inaccessible to microbial attack. However Fitts (1953) observed that soil aggregate size apparently had little effect upon nitrate production. He found approximately the same nitrification rate in hand mixed samples that contained aggregates < 2 mm or 0.85 mm diameter. Similar results were obtained by Hagin and Halevy (1961). The contradictory results found by various workers appear due to the fact that different soil types were used in different experiments and that the properties of the soil (e.g. organic matter content) may or may not vary with aggregate size (Craswell and Waring 1972).

SECTION 3. FIELD STUDIES

3.1 INTRODUCTION

The general objective of this investigation was to determine some physical and agronomic characteristics of seed-beds with well-defined structure. The observations and findings may help define more precisely the type of seed-bed suitable for cereals in semi-arid regions. The field studies carried out here examined the effects of the size and stability of aggregates in stratified seed-beds on: (a) germination, emergence and subsequent growth of wheat; (b) soil temperature and soil water potential in the seed-beds; and (c) soil structure and the changes of this structure with time at the surface of the seed-beds.

Seed-beds produced by tillage contain a wide range of aggregate sizes and they depend very much on the implement used and the state of the soil at the time of tillage. Such seed-beds are difficult to reproduce even when using the same implement, and the results obtained may not be generally applicable. For this reason, the seed-beds used in the present study were prepared from sieved aggregates with defined size ranges. Although seed-beds prepared in this manner cannot be directly compared with those prepared by tillage implements, the method enables a defined range of aggregate sizes to be examined and seed-beds can be readily reproduced in space and in time.

3.2 MATERIALS AND METHODS

3.2.1 Site

The field experiment was carried out at the Waite Agricultural Research Institute, South Australia (34°58'S, 138°38'S, altitude 122.5m) on a red-brown earth, Urrbrae loam (Stace *et al.* 1968). Details of some of the soil characteristics after Braunack (1979) and Shanmuganathan and Oades (1982) are as follows:

pH (1:5, H_2O)	5.4
Total C (%)	1.48
Total N (%)	0.15
Cation exchange capacity ($C\ g^{-1}$)	6.20
Total P (ppm)	316
Plastic limit (% w/w)	16.7
Dispersion index	5
Clay (%)	19.4
Silt (%)	31.3
Fine sand (%)	43.8
Coarse sand (%)	2.0

The area where the experiment was conducted was under pasture from 1974 to 1979.

3.2.2 Design and treatments

The experiment had a randomised block design with four replications and the treatments, which were arranged in a factorial combination, were: Seed-beds (4) and P.V.A. (2).
There were three stratified seed-beds 8 cm deep comprising two 4 cm layers of different-sized aggregates as follows

2 - 4 mm over < 2 mm diameter, hereafter 2 - 4/< 2 mm diameter

4 - 8 mm over < 2 mm diameter, hereafter 4 - 8/< 2 mm diameter

4 - 8 mm over 2 - 4 mm diameter, hereafter 4 - 8/2 - 4 mm diameter.

In addition, an unstratified seed-bed was prepared from unsorted aggregates of < 8 mm diameter.

The P.V.A. "Mowiol" (Hoechst, W. Germany) of 70,000 molecular weight was applied at the rate of 0.2 % to the aggregates in half the plots.

The treatments were allocated randomly to the plots within each block (replication) and the whole experiment was repeated in space four times to enable samples to be collected on four occasions during the year. The total number of plots was 128.

3.2.3 Procedures

3.2.3.1 Preparation of soil

Two areas of 16 m x 1 m at the site of the experiment were excavated to a depth of 8 cm. The soil was spread out to dry under cover and sieved when it was dry enough to pass through a 2 mm sieve without clogging. Half the soil was treated with P.V.A. solution, using a mist spray. A rotary sieve was used to separate the required aggregates into nominal size ranges of < 8 mm, 4 - 8 mm, 2 - 4 mm and < 2 mm diameter. The separated aggregates were placed in air-tight plastic buckets for storage until placement of aggregates into wooden framed plots of 50 x 50 cm. Water contents of soil aggregates were determined prior to placement of the aggregates into the plots.

The proportion of various sized aggregates in each sieved size range was determined by hand sieving the soil through a nest of sieves (Fig. 1).

3.2.3.2 Sowing and management of the experiment

On 10 July the lower layer (4 cm deep) of appropriate soil aggregates was placed into the plots. The aggregates were then brought to the same water content (18 %) by spraying the soil with a moist spray. A basal fertilizer [$(NH_4)_2$ SO_4, K_2 SO4, NH_4H_2PO4] which provided the equivalent of 40 kg ha^{-1} of N, P and K was included in the water added. Four hours later the soil was evenly compacted by applying a pressure of 2.8 kPa: an operator stood on a board placed on the soil.

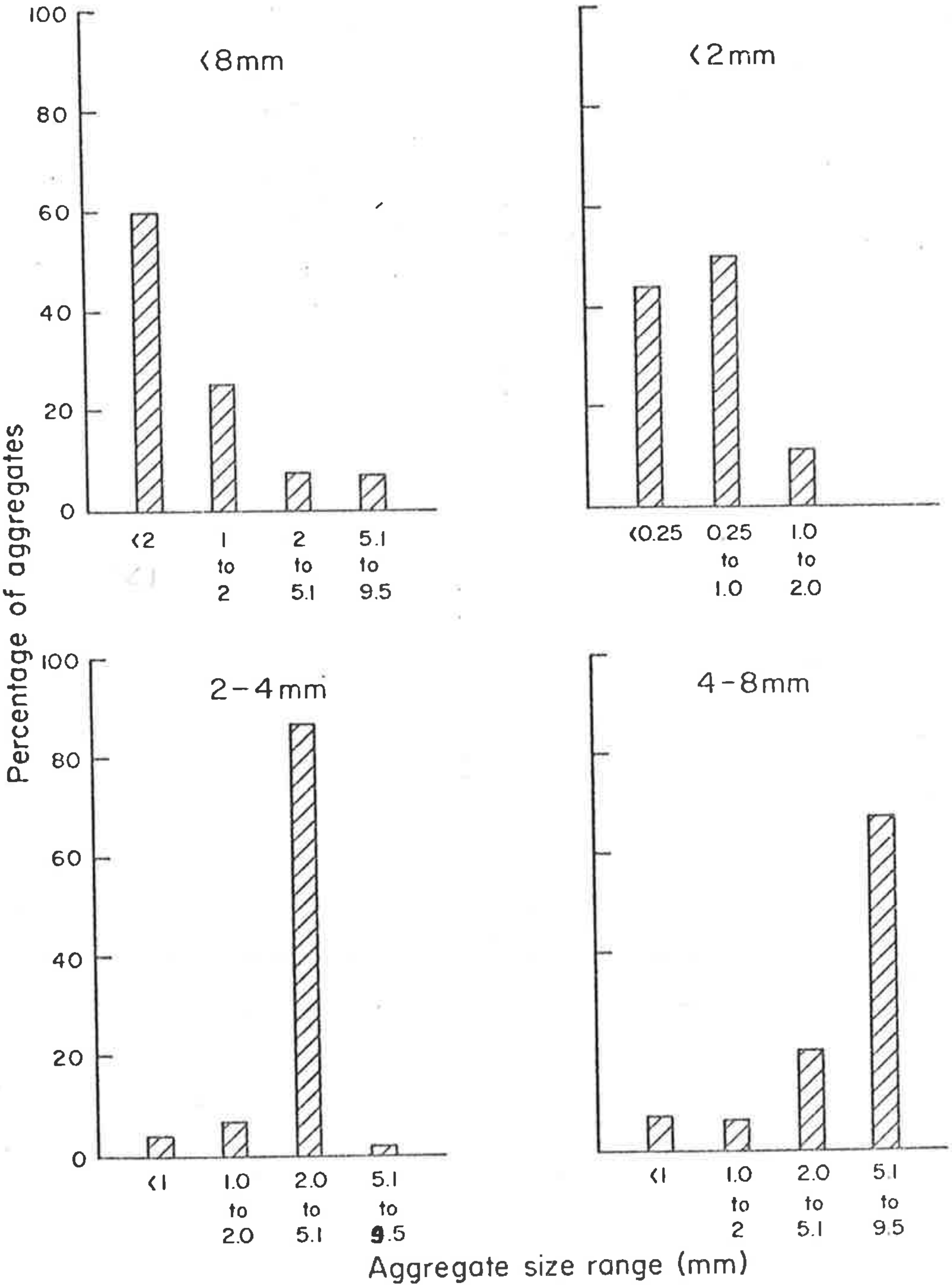

Fig. 1. Dry sieve analysis of aggregates obtained by rotary sieving into four size ranges.

On 11 July 100 seeds of wheat (*Triticum aestivum* L. c.v. Kite) were sown in each of the 128 plots. A board template with 10 rows of 10 evenly-spaced holes (5 cm centre to centre) was used to facilitate precise spacing during sowing. One seed was dropped through each hole onto the soil. The seeds were covered with 4 cm of the appropriate soil aggregates and the surface carefully levelled. The soil aggregates in the upper layer were then brought to the same water content (18 %) by spraying with a mist spray. The area around the experimental plots was sown with wheat to minimise edge effects. From emergence until harvest, the plots were covered with nets to prevent bird damage and consequent loss of yield. Plate 5 shows the layout of the experiment.

3.2.4 Measurement of soil structure

3.2.4.1 Collection of samples

For measurement of the macro-structure of the soil by the method of Dexter and Hewitt (1976), duplicate samples were collected for each treatment on 11 July, 14 July, 25 July and 20 September 1979 from the seed-beds. (These times corresponded to sowing, germination, emergence and tillering of the wheat.)

Metal moulds 42 cm long, 17 cm wide and 15 cm deep were pressed into the plots to 8 cm depth. The soil was impregnated with LC191 "Araldite" epoxy resin mixed with 10 % of HY951 hardener and 10 % of DW11 white pigment. Sufficient resin (about 3 l) was added to impregnate the soil and leave a layer about 10 mm thick on the surface to prevent soil blocks from breaking and to enable identification marks to be scratched on the resin layer. The samples were left on site for one day to cure. The impregnated blocks were then separated from the moulds and were cut twice vertically with a diamond saw. Cuts were made along the length of the blocks, about 5 cm from the edge to avoid edge effects.

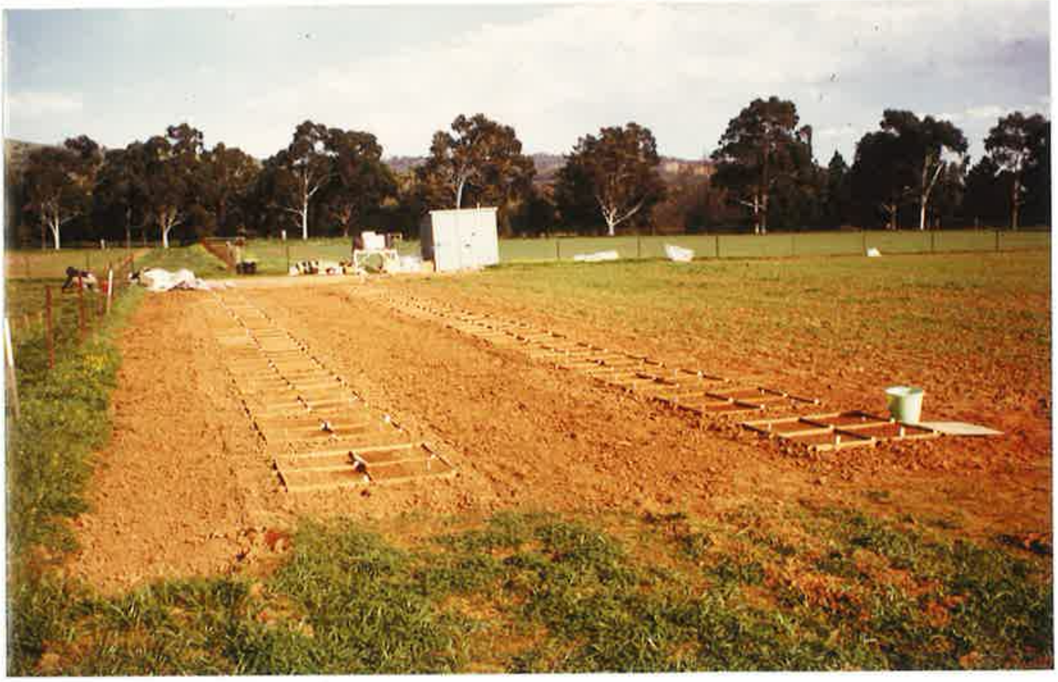

PLATE 5. General layout of the field experiment.

PLATE 6. Completed plot with thermistors and resistance blocks in place.

3.2.4.2 Method of measuring soil structure

Structural elements (intercepted pore size and intercepted aggregate size) were analysed along horizontal lines scratched (within 0.5 cm depth) on the face of each section. However measurements were not made on unsorted soil < 8 mm diameter sections as the resin did not adequately penetrate this soil. Grid points at 1 mm intervals across the section were designated 0 if they occurred on pores (white resin) or 1 if they occurred at aggregates. The macro-structure of the soil across 30 cm long sections of the soil was thus represented by a strong of 0's and 1's. Linear porosity, mean intercepted aggregate size and mean intercepted pore size were derived from this data using the statistical methods described by Dexter (1976).

It should be noted with respect to aggregates, that intercepted length is not the same as diameter obtained by sieving. Likewise, a mean intercepted pore size is a number average of the intercepted pore length rather than the mean diameter of the pores.

3.2.4.3 Soil penetrometer resistance and soil bulk density

Soil penetrometer resistance was measured at emergence (25 July) with a pocket penetrometer model CL-700 fitted with a cylindric steel probe 6.35 mm in diameter with a flat tip.

Bulk density was estimated at the same time as germination of the wheat occurred, by measuring with a ruler the depth from the soil surface to the seed.

3.2.5 Soil temperature and soil water

3.2.5.1 Measurement of soil temperature

Soil temperatures were recorded for two replications of each treatment at 0630 and 1500 h from shortly after sowing (14 July) to emergence (25 July) of the wheat, using a digital multimeter (Marconi instruments model TF 2670) and thermistors which had been installed at 4 and 8 cm depth in the seedbeds when the latter were prepared (Plate 6).

The resistance R of the thermistors varies as

$$R = Ae^{B/K}$$

when A and B are adjustable parameters and K is the absolute temperature. Rearranging gives

$$K = B/(\mathrm{Log}_e\ (R/A))$$

Hence, temperature ($^{\circ}$C)

$$T = B/(\mathrm{Log}_e\ (R/A)) - 273.2 \qquad (3.0)$$

B is the slope when Log_e R is plotted atainst 1/T and Log_e A is the intercept. The values of A and B were determined by calibration at 0 - 35°C in 5°C increments. A computer programme was written to calculate values of A and B for each thermistor used. Temperatures, measured in the field as electrical resistance, were then calculated. A typical calibration curve of temperature in Fig. 2

3.2.5.2 Measurement of soil water

Soil water potential was measured for two replications for each treatment at the same time as soil temperature, using a soil water and temperature bridge (National Instruments, Sydney, model 200) and gypsum resistance blocks installed at 4 cm depth in the seed-beds (Plate 6). The resistance blocks were calibrated in < 2 mm diameter aggregates at water potentials -10, -30, -70 and -100 kPa at constant temperatures of 15, 20 and 30°C. There was little difference in the response of different resistance blocks, and a mean calibration curve was used for all blocks to determine water potential in the field (Fig. 3). The relationship between soil water content and soil water potential is presented in the Fig. 4.

3.2.5.3 Meteorological data.

Records of air temperature Ta, wind speed W, relative humidity H, and rainfall R, were obtained from the Waite Institute meteorological

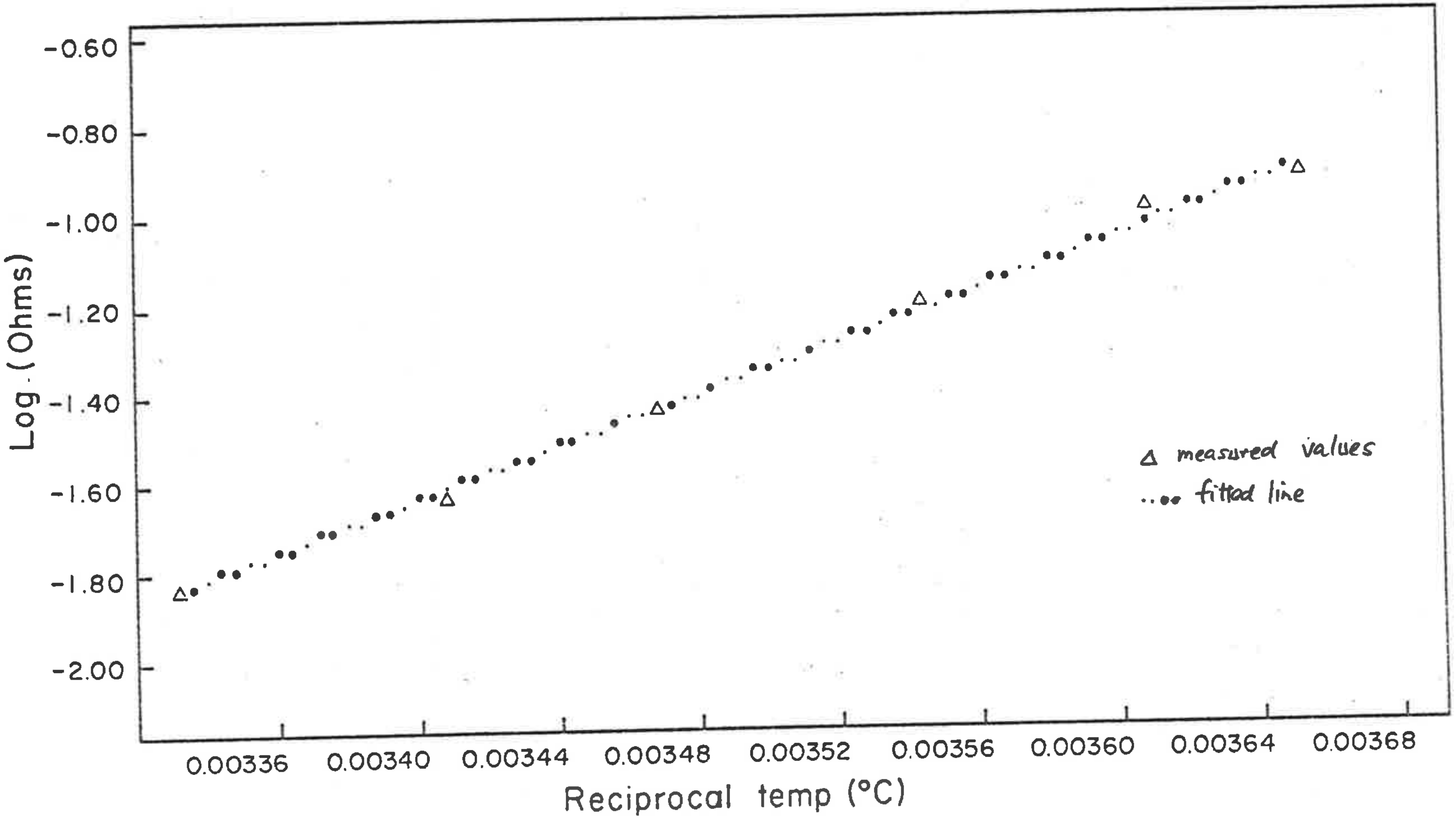

Fig. 2. Typical thermistor calibration curve for the determination of parameter in equation 3.0.

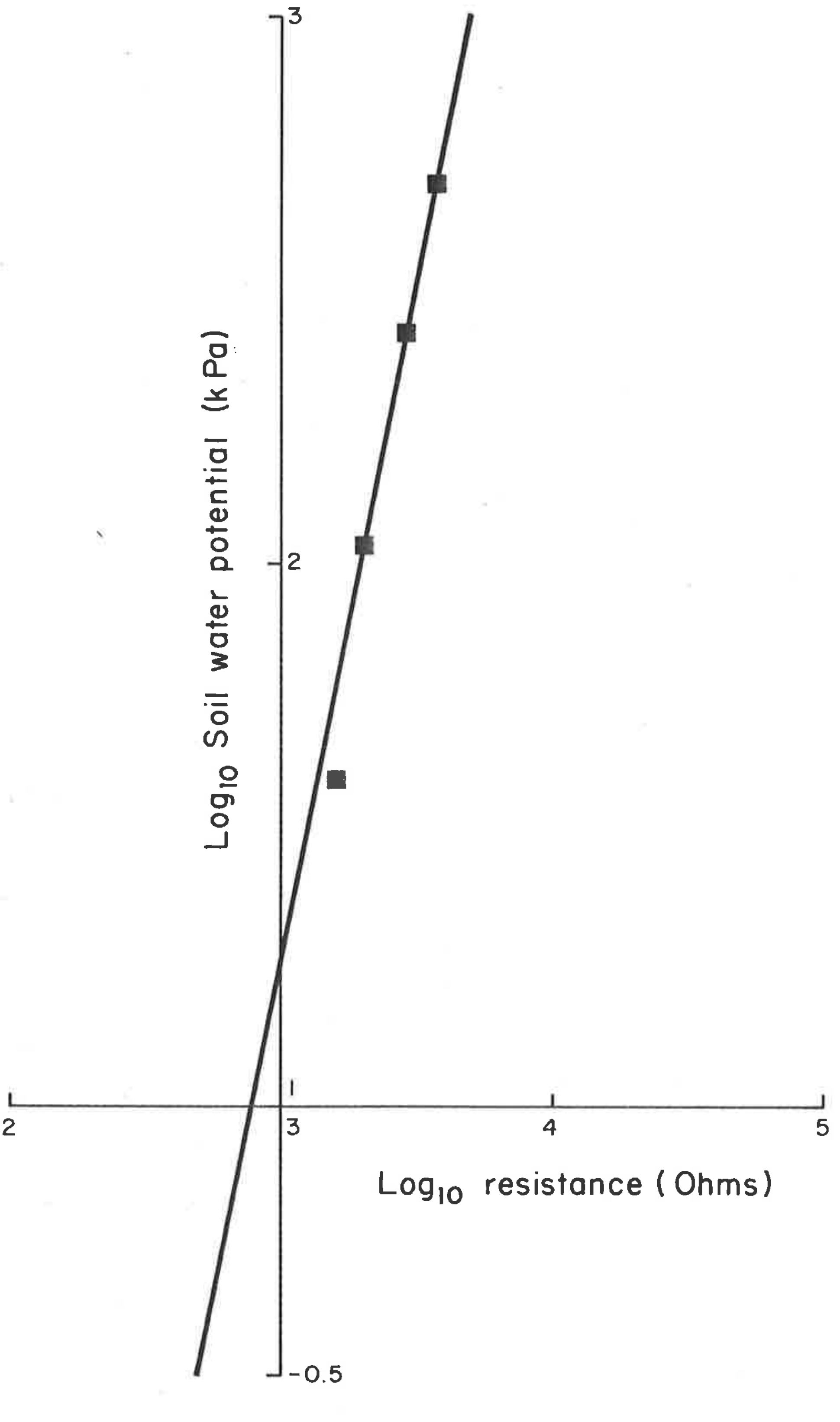

Fig. 3. Calibration curve for gypsum blocks.

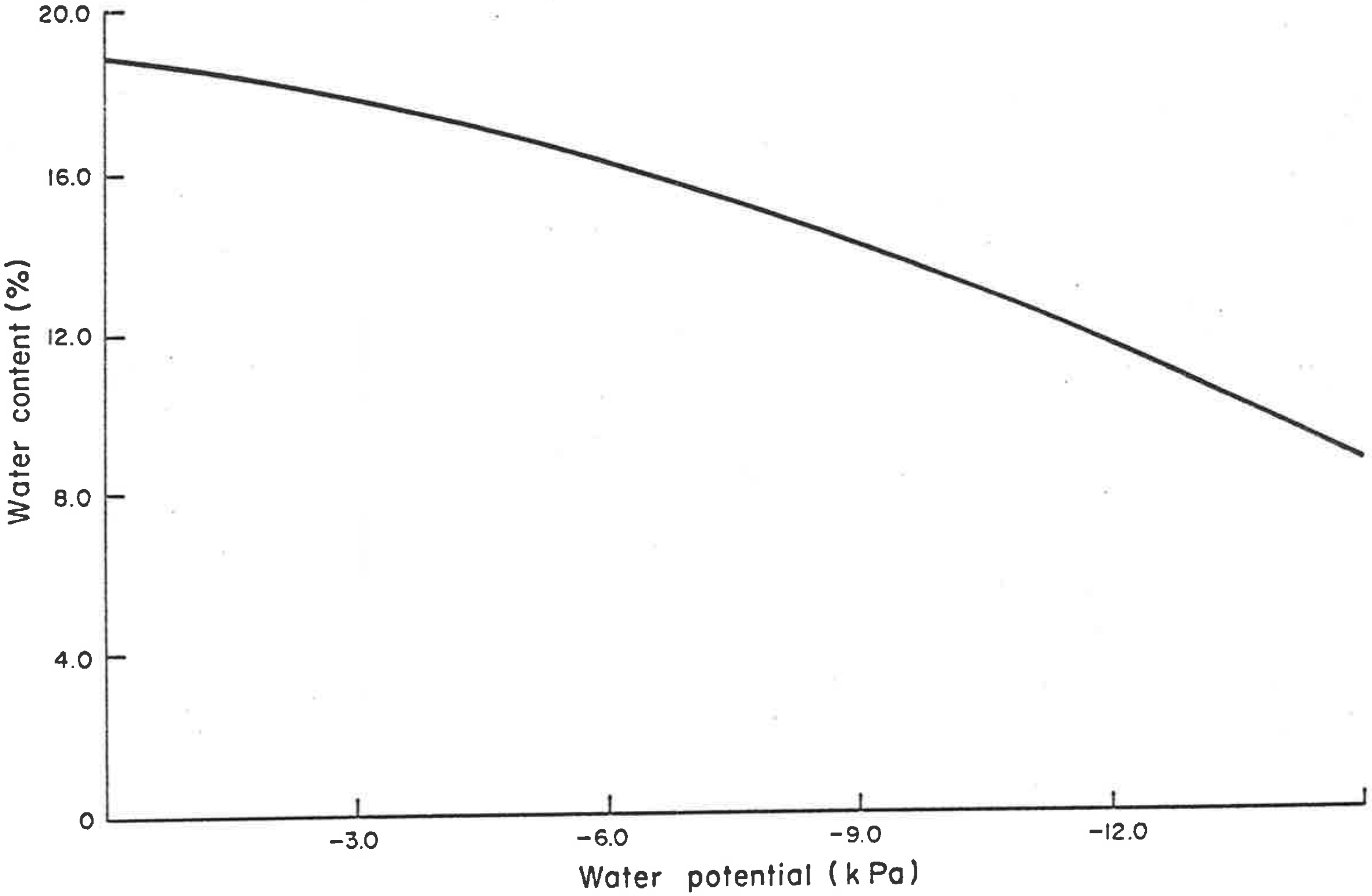

Fig. 4. Soil water potential - soil water content relationship for Urrbrae loam.

station located 300 m from the experimental site. Air temperature and relative humidity values were obtained from an automatic recorder 2 m above the ground level. Wind speeds were from an anemometer 2 m above the ground level. The rainfall was recorded daily with a pluviometer. Meteorological data are summarised in Table 3.0 and Fig. 5.

3.2.6 Plant growth measurements

In order to reduce edge effects, all measurements of plant growth excluded the outer rows of plants in each plots. Hence, instead of a 10 x 10 grid only 8 x 8 was considered i.e. 64 plants per plot.

3.2.6.1 Germination and emergence

To assess germination, two rows of seeds in each plot were examined each day from 15 July to 19 July. The number of seeds which had germinated was counted and percentage germination was calculated.

Emergence was assessed daily from 21 July to 31 July by counting the coleoptiles as they emerged through the surface of the soil. Percentage emergence was calculated.

The mean day of emergence (MDE), as defined by Edwards (1957a), was used as a measure of time between sowing and emergence. It was calculated for each plot by multiplying the number of coleoptiles which emerged each day by the number of days from sowing. The products were summed over the whole period of emergence and the total divided by the total number of the plants which had emerged on the plot to give the MDE for that plot.

3.2.6.2 Dry weight measurements

The number of plants per plot was counted at tillering (17 September) and at final harvest (5 December). The number of tillers per plant was also recorded.

TABLE 3.0. Meteorological data recorded at the Waite Agricultural Research Institute between 14 and 25 July 1979.

Mean daily values

Date of recording	T_a = Air temp. (^{o}C)	W = Wind speed at 2 m (km h^{-1})	H = Relative Humidity (%)	R = Rainfall (mm)
14 July	15.7	4.9	54	0.0
15 July	17.1	5.4	52	0.0
16 July	17.0	8.9	41	0.0
17 July	17.6	7.0	56	0.0
18 July	10.9	3.3	65	0.0
19 July	9.5	3.3	80	0.8
20 July	12.1	6.2	51	0.0
21 July	8.3	12.0	93	22.8
22 July	9.3	12.3	81	5.4
23 July	10.6	5.0	94	2.2
24 July	10.3	2.6	70	0.4
25 July	10.8	4.6	74	0.0

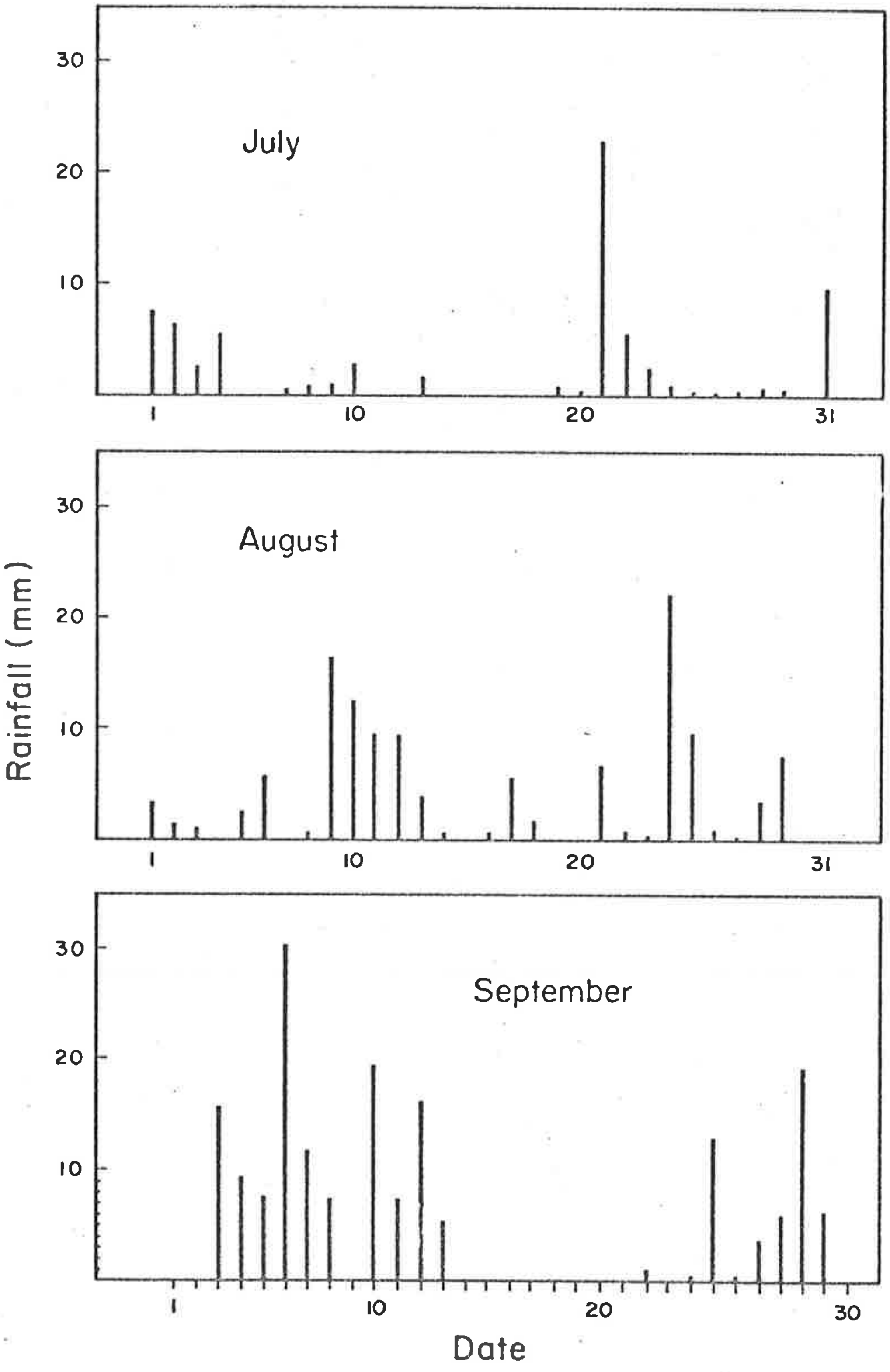

Fig. 5. Distribution of rainfall during three months of the growing season 1979 at the Waite Agricultural Research Institute.

The dry weight of the plants was measured at tillering and harvest. The plants were cut at ground level with shears, dried at $85^{o}C$ and weighed to determine total dry matter per plot. Following the December harvest, grain was separated with a resilient tapered thresher and weighed.

3.2.6.3 Nitrogen measurements

Subsamples of ground plant material - whole plant tops at tillering (17 September), and straw and grain at final harvest (5 December) - were digested with concentrated sulphuric acid and the nitrogen content of the digests determined by the alkaline phenate method (Keay and Menage 1970).

3.2.6.4 Root length measurement

Root length was measured at emergence and tillering. At emergence, whole plants were carefully dug out so the entire seminal and lateral roots were intact. The soil was washed from the roots with water over a fine sieve and the root length of each plant was measured with a ruler. The diameter of each seminal axis was measured 3 cm from the base of the plant, using a microscope with suitable scale. At tillering, four soil cores, 5 cm diameter and 60 cm long were taken from each plot. Root lengths in the 0 - 20, 20 - 40 and 40 - 60 cm depth intervals were determined using the intercept method of Newman (1966), after the roots had been separated from the soil by flotation.

3.3 RESULTS AND DISCUSSION

3.3.1 Soil structure

3.3.1.1 Results

Linear porosity at 0.5 cm depth in the seed-beds at sowing was similar for aggregates of 4 - 8 and 2 - 4 mm in diameter and it decreased with time. The minimum value occurred at emergence as indicated in Table 3.1. Aggregate size and P.V.A. treatment did not seem to have affected linear porosity at any stage of growth. At sowing, mean intercepted pore length was significantly higher ($P < 0.05$) in seed-beds made of aggregates 4 - 8 mm diameter than in seed-beds comprising aggregages of 2 - 4 mm diameter as indicated in Table 3.2. The same table shows that mean intercepted pore length declined from sowing to tillering, with minimum values occurring at emergence. The subsequent increase was not significant at $P < 0.05$.

Mean intercepted aggregate length increased steadily and significantly between sowing and tillering (Table 3.3). Mean intercepted aggregate length at emergence and at tillering was significantly ($P < 0.05$) affected by treatment of the soil with P.V.A.. Intercepted aggregate length in seed-beds, with initial aggregate size 4 - 8 mm diameter, was significantly higher when the aggregates were treated with P.V.A. Surprisingly, mean intercepted aggregate length was similar at time of sowing in beds of aggregates 2 - 4 and 4 - 8 mm diameter.

Table 3.4 indicates that the proportion of macropores > 1, > 2, > 4 and > 8 mm intercepted length declined between sowing and emergence. The proportion of pores > 1 and > 2 mm intercepted length was significantly higher at tillering than at emergence in both seed-beds made of aggregates 4 - 8 and 2 - 4 mm in diameter. At all times of sampling, the proportion of macropores > 1, > 2, > 4 mm intercepted length was significantly higher ($P = 0.05$) in seed-beds made of aggregates 4 - 8 mm in diameter than in seed-beds made of aggregates 2 - 4 mm in diameter.

The effect of P.V.A. treatment on pore size distribution in beds of aggregates 4 - 8 mm diameter is shown in the Table 3.5. The proportion of macropores > 1 and > 2 mm intercepted length is significantly higher ($P = 0.05$) in seed-beds made of aggregates treated with P.V.A. than in seed-beds made of untreated aggregates. This was true at all times of sampling except at tillering where there was no difference in the proportion of macropores > 1 mm intercepted length, in different seed-beds. Treatments had little effect on the proportion of pores with intercepted length > 4 mm. The proportion of macropores > 4 and > 8 mm intercepted length was low or nil at all times of sampling and in all treatments.

The changes in surface soil macroporosity with time are illustrated in Plates 1, 2, 3 and 4. The strength of the surface soil as measured by penetrometer resistance was significantly lower ($P = 0.05$) where the surface aggregates were 2 - 4 mm in diameter than for other sized aggregates (Table 3.6). Penetrometer resistance was significantly lower where the soil was treated with P.V.A. than for untreated soil except for aggregates 2 - 4 mm diameter. The bulk density of the surface 4 cm layer of aggregates was significantly higher ($P = 0.05$) in plots made of unsorted aggregates < 8 mm diameter than in all other treatments. P.V.A. treatment did not affect the bulk density of the soil.

Plates 7 to 12 illustrate the effect of raindrop impact on different sized surface aggregates, treated with P.V.A. (+ P.V.A.) or untreated (- P.V.A.), 5 days after sowing. The photographs show that the soil surface of seed-beds made of aggregates 2 - 4 mm diameter and not treated with P.V.A. are crusted and cracks appear on the soil surface. Seed-beds surface with unsorted aggregates < 8 mm in diameter were also crusted and cracks show on the soil surface. Surface aggregates 4 - 8 mm diameter treated with P.V.A. retained their shape as shown by the photographs.

TABLE 3.1. Temporal change in linear macro-porosity as affected by aggregate size and P.V.A. treatment.

Aggregate size (mm)	4 - 8		2 - 4	
P.V.A. treatment	0	0.2	0	0.2
Date and stage of growth	Linear porosity			
11 July (Sowing)	0.26	0.23	0.24	0.23
16 July (Germination)	0.13	0.19	0.12	0.18
27 July (Emergence)	0.04	0.05	0.06	0.09
20 September (Tillering)	0.10	0.14	0.08	0.10

L.S.D.(P = 0.05) = 0.11

TABLE 3.2. Temporal changes in mean intercepted pore length as affected by aggregate size and P.V.A. treatment.

Aggregate size (mm)	4 - 8		2 - 4	
P.V.A. treatment (%)	0	0.2	0	0.2
	Mean intercepted pore length (mm)			
11 July (Sowing)	2.76	2.64	2.07	1.95
16 July (Germination)	1.76	1.94	1.34	1.84
27 July (Emergence)	1.38	1.19	0.94	1.03
20 September (Tillering)	1.80	1.85	1.25	1.45

L.S.D. (P = 0.05) = 0.68

TABLE 3.3. Temporal changes in mean intercepted aggregate length as affected by aggregate size and P.V.A. treatment.

Aggregate size (mm)	4 - 8		2 - 4	
P.V.A. treatment (%)	0	0.2	0	0.2
	Mean intercepted aggregate length (mm)			
11 July (Sowing)	7.73	6.73	6.65	8.96
16 July (Germination)	11.84	12.13	12.48	14.17
27 July (Emergence)	19.48	13.66	14.42	14.91
20 September (Tillering)	24.83	15.56	18.61	21.83

L.S.D. (P = 0.05) = 3.93

TABLE 3.4. Temporal changes in intercepted pore length distribution expressed as the proportion of intercepted macropores larger than Xmm, as affected by aggregate size. All aggregates were treated with P.V.A.

	Aggregate size (mm)							
	4 - 8				2 - 4			
Date and stage of growth of wheat	Intercepted pore length (mm) = X							
	1	2	4	8	1	2	4	8
	Intercepted pore length distribution (%)							
11 July (Sowing)	0.73	0.46	0.14	0.01	0.57	0.26	0.08	0.00
16 July (Germination)	0.52	0.33	0.08	0.00	0.27	0.10	0.00	0.00
27 July (Emergence)	0.30	0.07	0.04	0.00	0.12	0.00	0.00	0.00
20 September (Tillering)	0.35	0.13	0.06	0.02	0.12	0.08	0.02	0.00

L.S.D. (P = 0.05) = 0.04

TABLE 3.5. Temporal changes in intercepted pore length distribution, expressed as the proportion of macropores larger than X mm, as affected by P.V.A. treatments. Aggregate sizes were 4 - 8 mm.

Date and stage of growth of wheat	P.V.A. treatment (%) 0				P.V.A. treatment (%) 0.2			
	Intercepted pore length (mm) = X							
	1	2	3	4	1	2	3	4
	Intercepted pore length distribution (%)							
11 July (Sowing)	0.71	0.42	0.16	0.00	0.77	0.49	0.19	0.02
16 July (Germination)	0.50	0.22	0.14	0.00	0.65	0.34	0.15	0.00
27 July (Emergence)	0.19	0.09	0.05	0.00	0.24	0.15	0.04	0.00
20 September (Tillering)	0.21	0.11	0.05	0.01	0.25	0.17	0.06	0.04

L.S.D. (P = 0.05) = 0.05

TABLE 3.6. Bulk density and penetrometer resistance as affected by aggregate size and P.V.A. treatment. Both measurements were done on 27 July (Emergence).

Aggregate size (mm)	4-8 / 2-4		4-8 / < 2		2-4 / < 2		Unsorted < 8		L.S.D. P=0.05
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2	
Bulk density g cm^{-3}	0.96	0.93	0.95	0.94	0.94	0.94	1.08	1.05	0.03
Penetrometer resistance (kPa)	33.5	26.9	32.1	25.5	23.8	22.2	35.0	29.3	4.21

PLATE 1. Changes in soil structure with time.
The initial aggregate size range was 4 - 8 mm.
The soil was untreated with P.V.A.
Sampling was done from (top to bottom) at sowing (11 July), germination (14 July), emergence (20 July) and tillering (20 September).

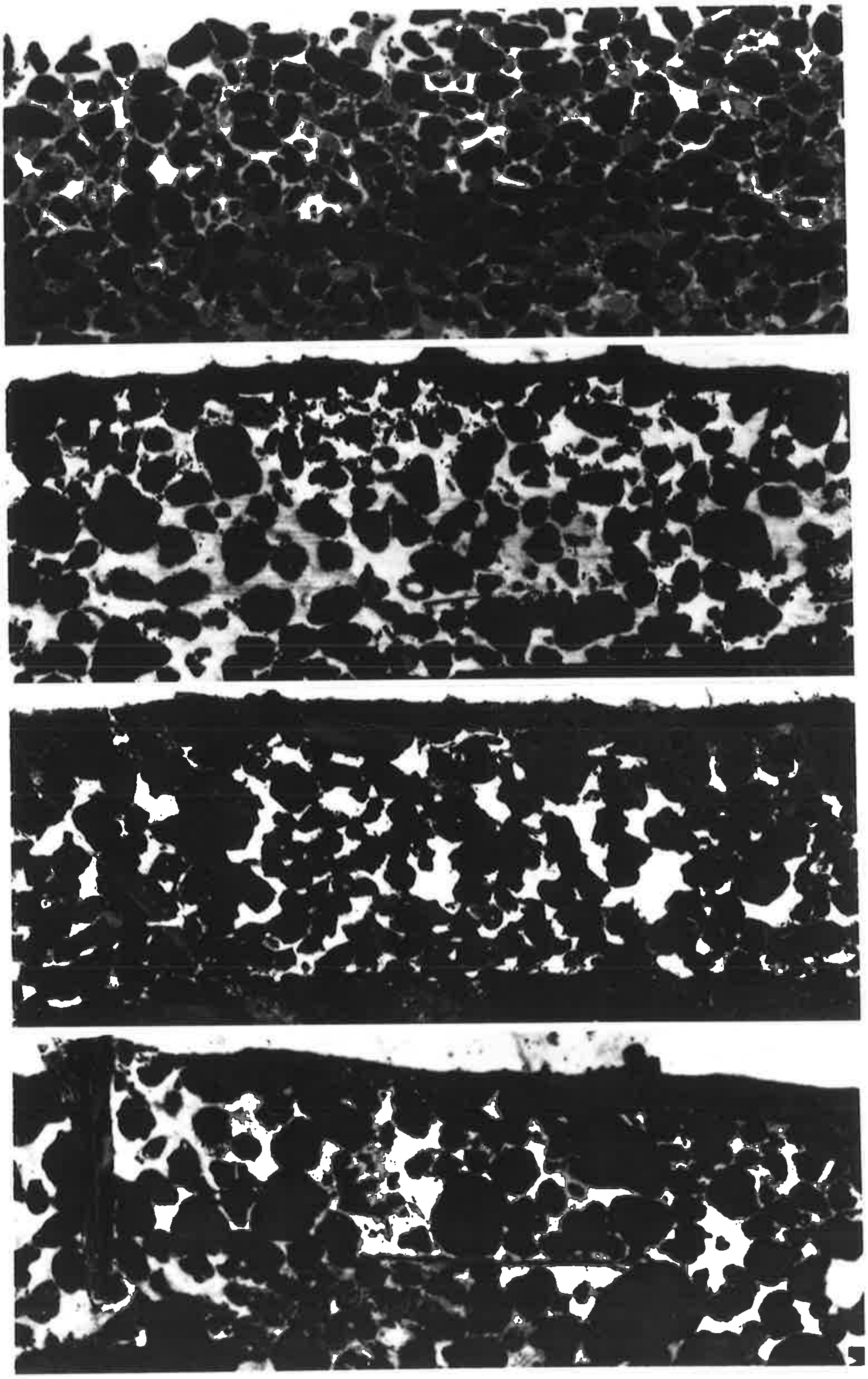

PLATE 2. Changes in soil structure with time.
The initial aggregate size was 4 - 8 mm.
The soil was treated with P.V.A.
Sampling was done (from top to bottom) at
sowing (11 July), germination (14 July),
emergence (20 July) and tillering (20 September).

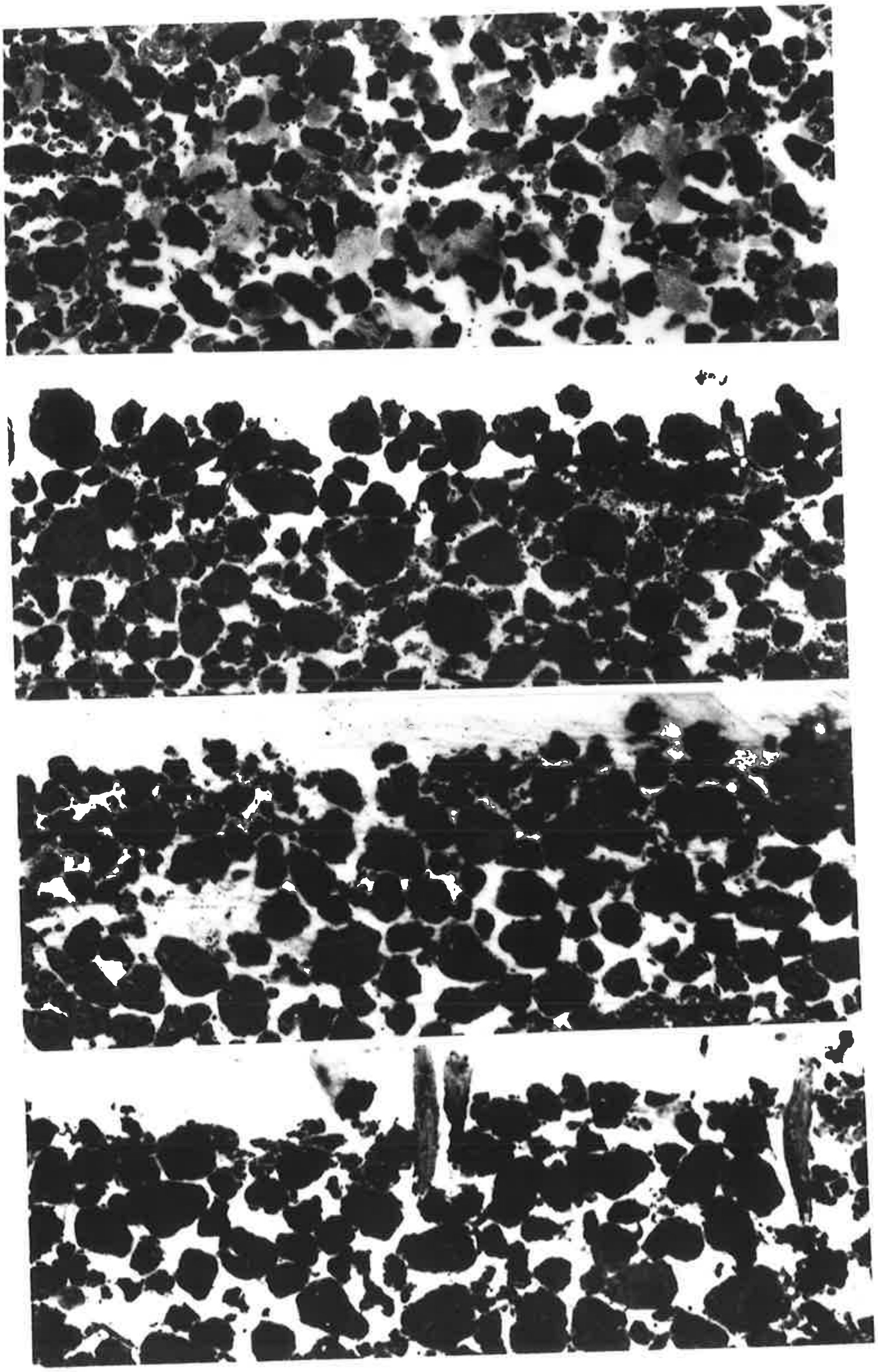

PLATE 3. Changes in soil structure with time.
The initial aggregate size was 2 - 4 mm.
The soil was untreated with P.V.A.
Sampling was done (from top to bottom) at sowing (11 July), germination (14 July), emergence (25 July) and tillering (20 September).

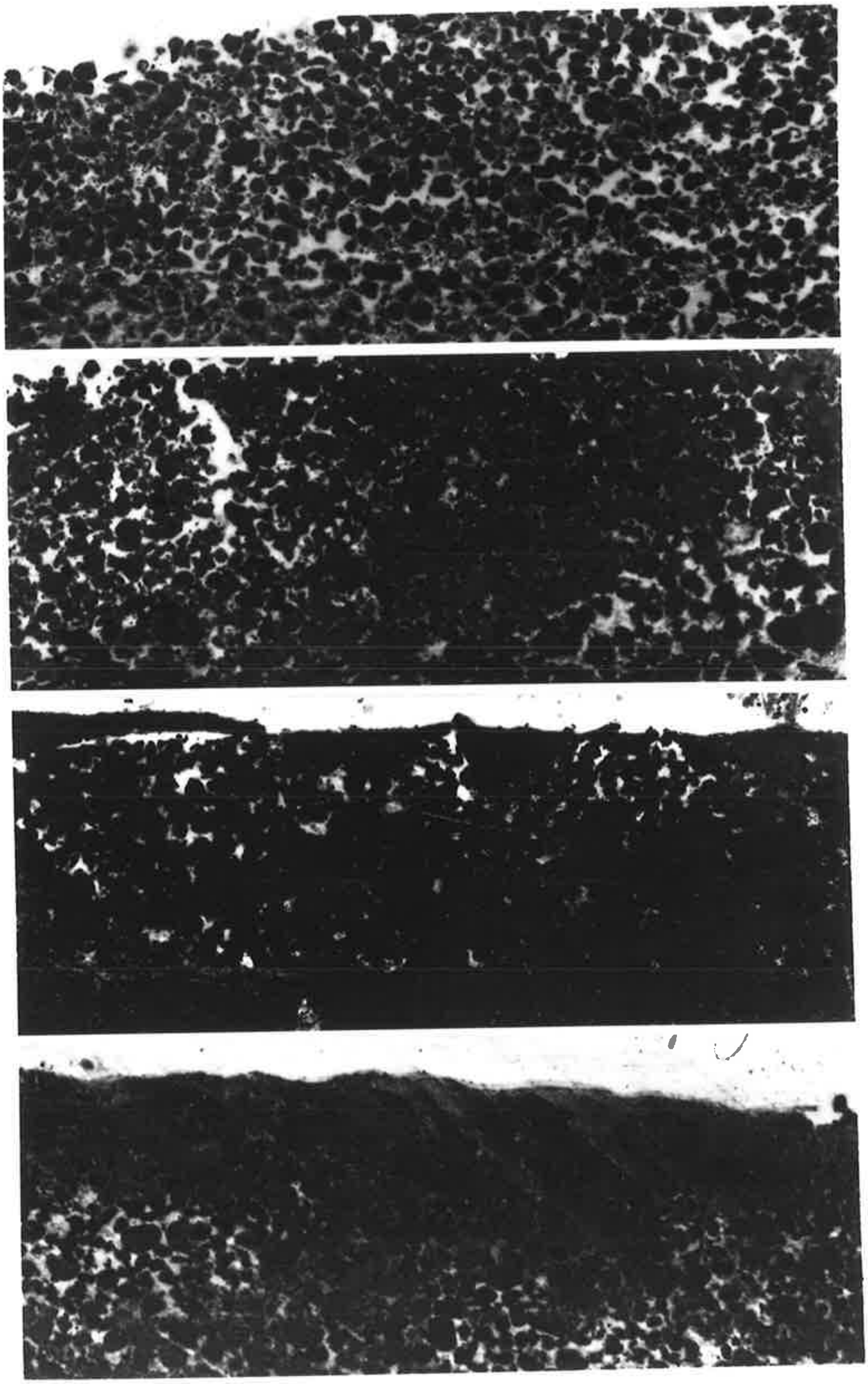

PLATE 4. Changes in soil structure with time.
The initial aggregate size was 2 - 4 mm.
The soil was treated with P.V.A.
Sampling was done (from top to bottom) at sowing (11 July), germination (14 July), emergence (25 July) and tillering (20 September).

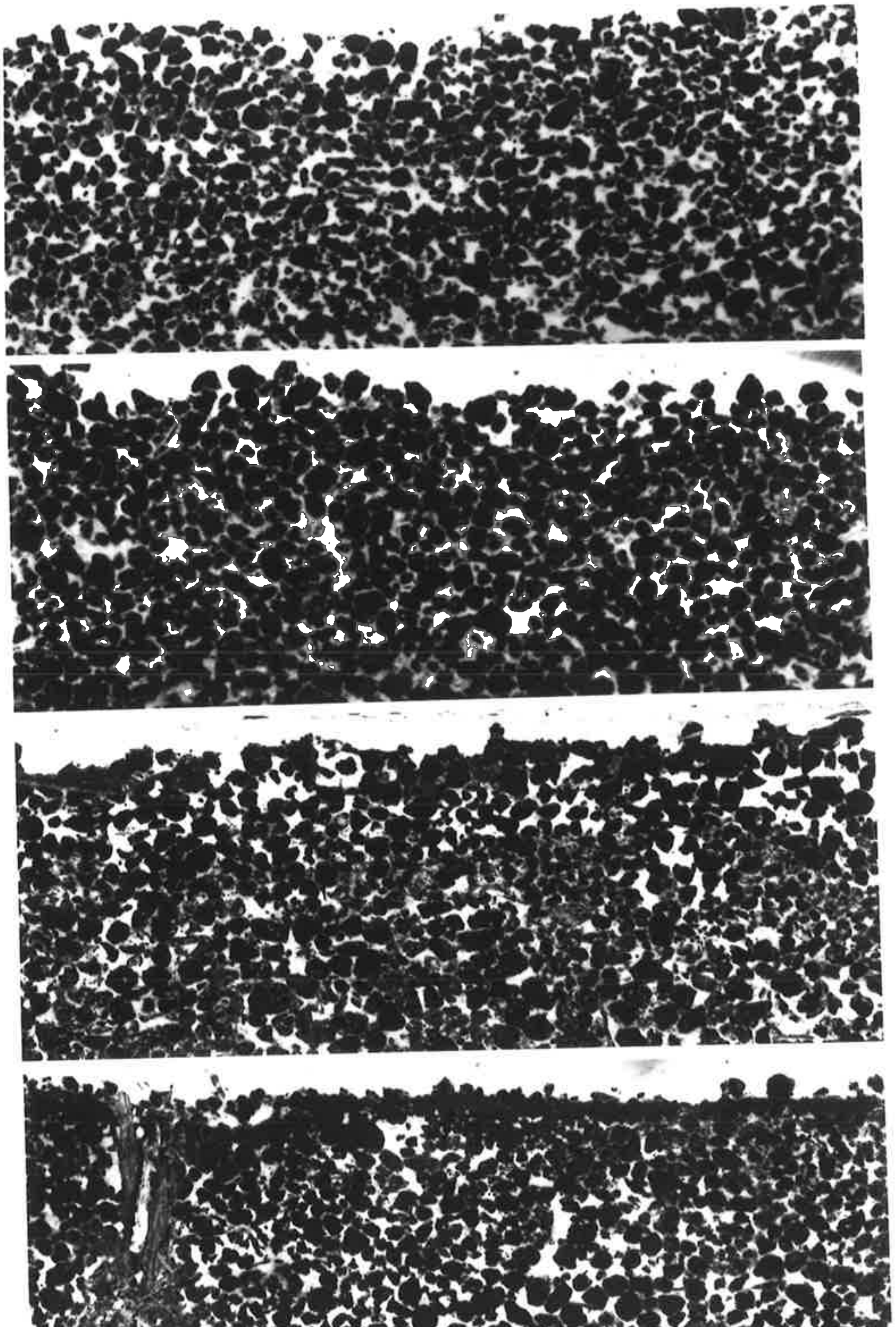

PLATE 7. Plots made of aggregates 4 - 8/2 - 4 mm untreated with P.V.A., 5 days after sowing.

PLATE 8. Plots made of aggregates 4 - 8/2 - 4 mm treated with P.V.A., 5 days after sowing.

PLATE 9. Plots made of aggregates 2 - 4/< 2 mm untreated with P.V.A., 5 days after sowing.

PLATE 10. Plots made of aggregates 2 - 4< 2 mm treated with P.V.A., 5 days after sowing.

PLATE 11. Plots made of unsorted aggregates < 8 mm untreated with P.V.A., 5 days after sowing.

PLATE 12. Plots made of unsorted aggregates < 8 mm treated with P.V.A., 5 days after sowing.

3.3.1.2 Discussion

The impact of raindrops causes the breakdown of aggregates into micro-aggregates which fill the surface macropores creating a smooth surface which hardens into a crust upon drying. This is illustrated in Plates 7 to 12, and by the results in Tables 3.1, 3.2 and 3.4, which show the effect of aggregate breakdown on the soil macroporosity at the 0.5 cm depth in the seed-beds. Changes in soil structure, and in particular changes in macroporosity occurred mainly within the top 0.5 cm of the seed-bed profile (Plates 1, 2, 3 and 4). This is in agreement with the observations of Collis-George and Lal (1970) and Ojeniyi (1978). The breakdown of aggregates increased with decreasing the size of aggregates as illustrated by Plates 7 to 14. Results in Table 3.4 confirm that the distribution of pores > 1, > 2, and > 4mm intercepted length at 0.5 cm depth in the seed-beds decreased with decreasing initial aggregate size from 4 - 8 to 2 - 4 mm size range. Ojeniyi (1978), using the same method of soil structure measurement as the one used here, found similar results when seed-beds were prepared in the same soil by tillage. He found that the proportion of pores larger than 8 mm intercepted length was greater in tilths produced by ploughing than in those produced by a rotary cultivator or a scarifier. He concluded that greater proportion of larger pores in the tilths produced by ploughing was because the tilth had larger aggregate sizes at the surface of the seed-bed than either those produced by the rotary cultivator or scarifier.

Most of the surface aggregates 4 - 8 and 2 - 4 mm diameter treated with P.V.A. kept their initial shape for two weeks while the untreated aggregates had broken into smaller aggregates. The breakdown of macro-aggregates has led to a greater decrease in the distribution of intercepted pores > 1, and >2mm intercepted length in the seed-bed surface with aggregates not treated with P.V.A. compared to the P.V.A. treated ones (Table 3.5). Similar observations were made by Mazurak and

Mosher (1970) when aggregates 4.20 and 2.97 - 2.10 mm diameter aggregates were treated with "Krilium" to obtain water-stable aggregates.

The linear porosity and mean intercepted pore length which decreased steadily between sowing (July 11) and emergence (27 July) increased slightly at tillering (20 September). The amount and intensity of rainfall which fell between germination (16 July) and emergence (25 July) (Fig. 5) caused a decrease of 70 % and 50 % of the initial linear porosity of the seed-bed surface when the initial aggregate size was 4 - 8 and 2 - 4 mm respectively (Table 3.1). This reduction in linear porosity is especially marked when aggregates were not treated with P.V.A. and where the surface crust has formed. The reduction in surface macroporosity due to crust formation can result in a severe decrease of water infiltration and increase in run-off as observed by Oades (1976), and the emergence of plants can be reduced or inhibited upon the drying and hardening of the crust. The slight increase in linear porosity and mean intercepted pore length which occurred at tillering may be attributed to the mechanical effects of the growing plants and cracking of the crust. There was no evidence of any run-off on the present experiment. Over the period when measurements were made rainfall intensity was not sufficiently high for it to occur (Fig. 5). Braunack (1979) found that when rainfall was applied at 27 mmh^{-1}, the time to run-off for aggregates > 4 and 4 - 2 mm diameter from Urrbrae loam, was 25 and 15 min respectively.

In conclusion, it may be stated that the macroporosity decreased from sowing to emergence (although it increased slightly thereafter) and that the changes were greatest in seed-beds not treated with P.V.A.. A greater proportion of intercepted pores > 1, > 2, and > 4 mm was found at all times of measurements in the surface of seed-beds with initial aggregate sizes 4 - 8 mm than in seed-beds with initial aggregate size 2 - 4 mm diameter. The proportion of intercepted macropores > 1, and > 2 mm intercepted length was higher when soil aggregates were treated with P.V.A. than when they were not treated with P.V.A.. The relationship between soil structure, soil physical conditions and plant growth are discussed subsequently.

3.3.2 Soil temperature and water potential

3.3.2.1 Results

The effects of aggregate size and P.V.A. treatment on soil temperature at 4 and 8 cm depth during the period 14 to 25 July (from sowing to emergence of wheat), are summarised in Tables 3.7 and 3.8. At both depths (4 and 8 cm), there was little difference in soil temperature between different aggregate sizes. Aggregates not treated with P.V.A. tended to be slightly warmer than the aggregates treated with P.V.A. However this difference was less than 1°C. Temperature at 8 cm depth tended to be slightly higher than at 4 cm depth except for the unsorted aggregates < 8 mm diameter.

Table 3.9 summarises the mean daily water potential (mean of data recorded at 0630 and 1500 hours). During the period 14 to 25 July, the soil was generally drier in seed-beds made of aggregates 4 - 8/2 - 4 mm and 4 - 8/<2 mm diameter than in seed-beds made of aggregates 2 - 4/<2 mm and of unsorted aggregates <8 mm diameter. The mean water potential of the soil in seed-beds made of aggregates 2 - 4/<2 mm and unsorted <8 mm diameter were significantly ($P = 0.05$) higher than seed-beds made of aggregates 4 - 8/<2 - 4 mm or 4 - 8/<2 mm diameter. Seed-beds with aggregates treated with P.V.A. were drier (though not significantly) than seed-beds with aggregates untreated with P.V.A.

TABLE 3.7. Soil temperature at 4 cm depth. Mean of temperature recorded at 0630 and 1500 hours from 17 to 25 July 1979.

Agg. size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		< 8	
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2
Date of recording	Temperature (°C)							
14 July	16.6	16.4	17.2	16.7	16.3	15.6	16.6	17.3
15 July	13.0	12.3	11.9	12.2	12.5	11.8	12.5	12.5
16 July	13.4	12.9	13.0	13.1	13.0	12.9	13.3	13.4
17 July	13.3	12.0	13.3	13.4	13.5	11.9	14.1	14.6
18 July	11.4	11.3	12.7	10.9	11.6	11.2	12.6	12.2
19 July	10.9	10.0	10.7	9.6	12.2	10.5	11.2	11.6
20 July	11.0	9.9	10.1	9.4	10.9	9.0	9.2	10.2
21 July	10.5	9.3	10.2	9.9	10.3	9.5	10.4	10.6
22 July	9.5	9.1	10.0	9.6	9.7	9.0	10.7	10.4
23 July	10.9	10.9	11.1	11.2	11.7	10.1	11.6	11.1
24 July	10.3	9.8	10.2	10.5	10.5	9.6	10.7	10.9
25 July	9.7	9.6	9.9	10.0	9.5	9.5	9.9	10.3

L.S.D. (5%) = 2.0

Mean	11.7	11.2	11.7	10.9	11.2	10.8	11.9	12.1

L.S.D. (P = 0.05) = 0.9

TABLE 3.8. Soil temperature at 8 cm depth. Mean of temperature recorded at 0630 and 1500 hours from 14 to 25 July 1979.

Agg. size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		< 8	
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2
Date of recording	Temperature (^{o}C)							
14 July	17.2	15.8	15.6	16.0	16.1	15.6	16.4	16.4
15 July	12.4	12.4	12.5	12.4	12.7	12.1	11.5	11.6
16 July	13.1	13.3	11.7	12.9	12.5	12.2	11.1	12.8
17 July	14.0	13.3	14.1	13.2	13.4	12.4	13.3	13.5
18 July	16.0	13.0	13.2	15.2	12.7	13.3	14.1	14.1
19 July	12.0	11.9	10.9	11.2	10.1	9.5	10.7	10.3
20 July	11.1	10.9	10.2	9.6	9.7	9.6	9.5	10.1
21 July	10.5	10.3	11.4	9.9	10.3	9.6	9.8	10.2
22 July	10.3	10.0	11.0	9.8	10.0	9.6	9.2	9.8
23 July	11.1	11.1	11.2	10.7	10.7	10.7	9.8	10.7
24 July	10.8	11.5	11.4	10.9	10.8	10.7	11.4	10.7
25 July	10.2	10.2	10.2	10.1	10.6	10.3	10.3	10.8
L.S.D. (5%) = 2.4								
Mean	12.4	12.0	12.1	11.8	11.9	11.4	11.4	11.0
L.S.D. (P = 0.05) = 0.9								

TABLE 3.9. Water potential of different seedbeds at 4 cm depth. Mean of water potential recorded at 0630 and 1500 hours from 14 to 25 July 1979.

Agg. size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		< 8	
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2
Date of recording	Water potential (kPa)							
14 July	-42.4	-62.3	-52.5	-60.6	-47.1	-46.1	-48.8	-55.6
15 July	-44.1	-65.1	-46.0	-60.1	-41.7	-42.5	-44.3	-50.6
16 July	-58.3	-59.6	-49.9	-50.0	-49.0	-46.4	-43.5	-46.4
17 July	-24.6	-14.8	-20.7	-19.2	-12.2	-12.0	-13.2	-12.3
18 July	-28.4	-20.3	-24.8	-21.6	-17.9	-15.6	-19.1	-15.2
19 July	-36.6	-33.8	-29.7	-35.2	-26.6	-30.7	-24.5	-23.8
20 July	-41.3	-45.3	-43.0	-39.5	-33.3	-33.5	-35.3	-35.7
21 July	-26.1	-28.8	-21.3	-17.6	-13.7	-13.6	-15.0	-17.4
22 July	-25.1	-24.1	-20.1	-20.1	-12.7	-12.5	-17.1	-16.4
23 July	-25.2	-20.0	-20.4	-20.5	-15.6	-13.0	-17.1	-16.5
24 July	-26.2	-24.3	-20.4	-21.2	-20.7	-19.3	-18.1	-19.4
25 July	-23.4	-27.3	-23.5	-22.7	-23.1	-16.8	-20.2	-19.4

L.S.D. (5%) = 3.9

Mean	-33.5	-35.5	-31.0	-34.2	-20.3	-25.2	-26.4	-27.4

L.S.D. (P = 0.05) = 5.2

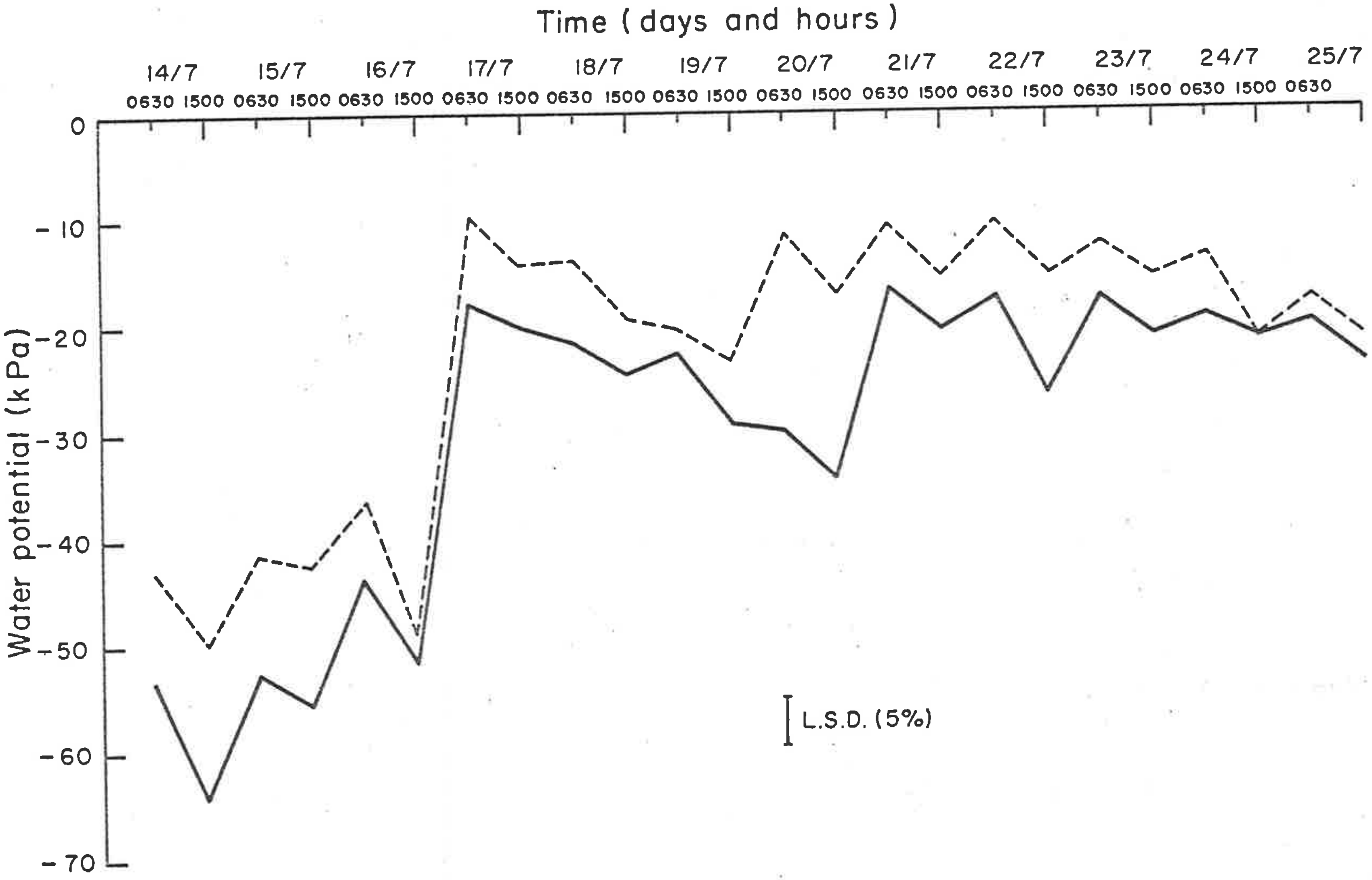

Fig. 6. Water potential at 4 cm depth (seed level) in seed-beds made of aggregates 4 - 8/< 2 mm (——) and 2 - 4/< 2 mm (---) at 0630 h and 1500 h from 14 to 25 July. (Mean of 0 % and 0.2 % P.V.A. treatments)

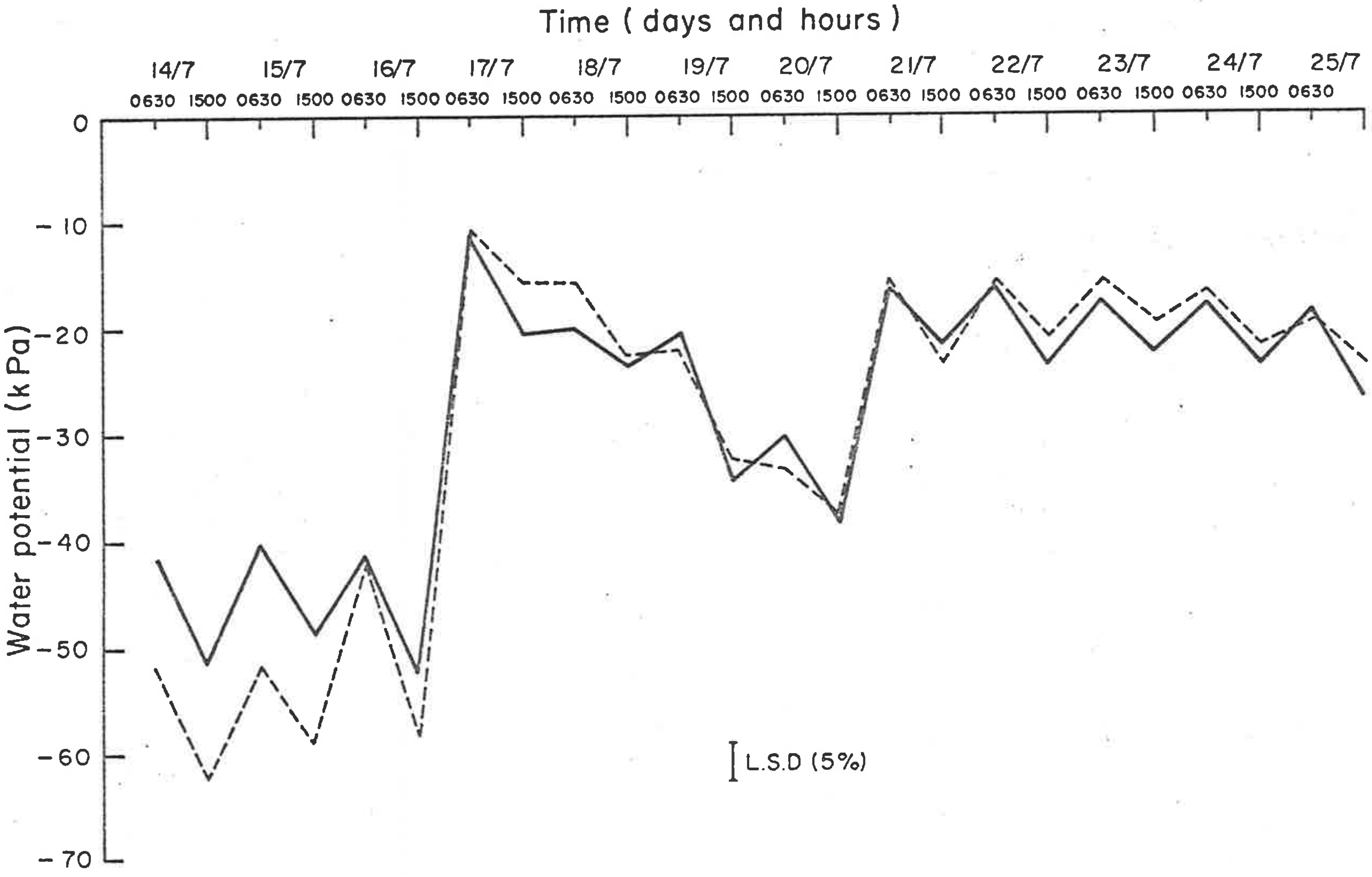

Fig. 7. Water potential at 4 cm depth (seed level) at 0630 and 1500 h from 14 to 25 July with (---) and without (——) P.V.A. treatments.
(Mean of all aggregate treatments)

3.3.2.2 Discussion

All seed-beds made with different aggregate sizes had similar temperatures during the time the temperature was recorded. However, the mean temperature at 8 cm depth was higher than that at 4 cm depth. The greatest variations in temperature due to meteorological effects occur in the top layer of the seed-bed (Hay 1977). The difference between the highest and the lowest mean temperature recorded was 1.3 and 1.4°C at 4 and 8 cm respectively; however, on a whole-plot basis this difference is only 0.95. The differences in soil water in different seed-beds was not reflected in the soil temperature. This is probably because differences in soil water content were small, and not high enough to affect the temperature of the soil significantly.

All seed-beds were drier at 1500 h than at 0630 h (Fig. 6 and 7). This is the expected trend as the soil dries during the day and becomes wetter at night (Rose 1968).

At both 4 and 8 cm depth, soil temperature was unaffected by the aggregate size in the range used here. A similar observation was made by Braunack (1979) for aggregate sizes of similar range. However, Allmaras *et al.* (1972) noted that when seed-beds were prepared by tillage, those with a rough surface with large aggregates (proportion and sizes not given) were much cooler than seed-beds with a smoother surface and smaller aggregates. These large differences of soil temperatures found by Allmaras *et al.* (1972) are because seed-beds with large surface aggregates (clods) experience great changes in temperature due to convective processes (Ojeniyi 1978), but in the experimental study undertaken here, the aggregate size range used was narrow and the sizes were much smaller than those measured by Allmaras *et al.* (1972) and Ojeniyi (1978).

The plots with aggregates not treated with P.V.A. were slightly warmer than the plots treated with P.V.A. (Table 3.7) possibly because the plots with aggregates not treated with P.V.A. had a crusted surface which had an insulating effect against the wind and air temperature. On the other hand, plots treated with P.V.A. were slightly drier than the untreated ones (Table 3.9 and Fig. 7) and should heat more quickly. The fact that seed-beds made of aggregates 2 - 4/< 2 mm and unsorted aggregates < 8 mm diameter were the wettest during the period from germination (14 July) to emergence (25 July) (Fig. 6) can be explained by the lower evaporation likely to be exhibited by these sizes of aggregates (Hillel and Hadas 1972; Hadas 1975; Braunack 1979). Better penetration of turbulent air currents into inter-aggregates cavities in the case of large aggregates, and a better water conductance in the case of smaller aggregates are responsible for the observed effects (Holmes *et al.* 1960; Hillel and Hadas 1972; Hadas 1975; Braunack 1979).

An equation relating soil temperature T_s, soil water potential Ψ (kPa) and meteorological factors was developed by Decker (1957) as follows:

$$T_s = a + b\Psi + cT_a + dW = eH \qquad (3.1)$$

where a, b, c, d and e are adjustable parameters and Ψ, the soil water potential (kPa), T_a the air temperature (°C), W the wind speed (km h^{-1}), to H the relative humidity (%). The data in Table 3.0 was fitted to equation 3.1

$$T_s = 12.4 - 0.0584\Psi + 0.0159T_a - 0.0309W - 0.0399H$$

The multiple correlation between soil temperature and meteorological factors was 0.64. Soil water potential Ψ, wind speed W and air humidity H were negatively correlated with soil temperature. The correlation coefficients were respectively 0.58, 0.16 and 0.53. The effect of air temperature on soil temperature is negligible compared with the effect of soil water potential. Wind speed and air humidity have a lesser effect on soil temperature than soil water potential. These results agree well with those obtained by Decker (1957) and Braunack (1979) except for the wind

An equation relating soil water potential Ψ (kPa) and meteorological factors was developed by Rohwer (1931) as follows:

$$\Psi = a(1 + bW)(Ps - Pa) + k \qquad (3.2)$$

where a, b and k are adjustable parameters, W the wind speed (km h^{-1}) and Ps - Pa (kPa) is the vapour deficit with Ps being the equilibrium vapour pressure in the soil atmosphere. The values of Ps and Pa are obtained as follows:

$$Ps = Po \exp(-M\Psi / \ell RT) \qquad \text{(Rohwer 1931)}$$

where Po is the saturated vapour pressure of the water at a given temperature, M the molecular weight of water, (18 kg), Ψ the water potential of the soil (kPa), ℓ the density of water (1000 kg m^{-3}), T - 273.2^{o}K, R is the gas constant (8.314 x 10^3J K^{-1} kg-mole^{-1}). The vapour pressure of water in the atmosphere was determined from the relation

$Pa/Po = H$ (Rohwer 1931) where H is the humidity and Po is the saturated vapour pressure of the free water at the same temperature (air temperature). Values of Po were obtained from tables in the Handbook of Physics and Chemistry (Weast 1973).

Soil water potential was related to the meteorological data as follows:

$$\Psi = 0.03 - 1.00\ (Ps - Pa) - 0.0036W\ (Ps - Pa)$$

The equation shows that the effect of wind speed W, on soil water potential is negligible compared with the effect of water pressure deficit (Ps - Pa). According to the equation water potential in the soil decreases (becomes more negative) when (Ps - Pa) increases and vice versa. (Ps - Pa) was always positive during the period soil water potential was recorded. One would expect that the influence of the wind speed on soil water potential to be at a maximum when the soil was bare and when there is more air movement at the soil surface and its effects to be minimal when the soil is covered by the crop. When soil is covered by the crop, air temperature will become more important in influencing soil water potential than wind speed. However, in the case of this experiment, the effect of wind speed on water potential was minimal even when the soil was bare. It can be concluded that in the case of this experiment, aggregate size and P.V.A. treatments had only small effects on temperature and water content of the soil the most important of which was that seed-beds made of smaller aggregates (2 - 4/2 mm) remained the wettest during the period 14 to 25 July (germination to emergence). Meteorological factors, particularly air humidity water pressure deficit, were significant in influencing soil temperature and soil water potential.

3.3.3 Plant Growth

3.3.3.1 Results

A germination test in the laboratory showed the wheat seed to be 96.9 ± 0.28 % viable.

Table 3.11 shows that the percentage of seed which germinated in the field was little affected by aggregate size or by application of P.V.A. to the soil. There was no significant effect ($P = 0.05$) of the treatments on the percentage of plants which emerged. However the treatments did affect the rate of emergence. Seedlings emerged significantly earlier in plots comprising unsorted aggregates (< 8 mm diameter) and aggregates of 2 - 4/< 2 mm diameter than in other plots (Table 3.12). In the former plots emergence was significantly earlier ($P = 0.05$) where the soil had been treated with P.V.A.

There was a decline of about 10 % in the number of the wheat plants during the season and although there were some differences in percentage survival associated with treatments, they were not consistent between tillering and harvest (Table 3.11).

Table 3.12 shows that, in the range of aggregates used in this experiment, emergence was 0.75 and 0.55 day earlier in plots comprising aggregates 2 - 4/< 2 mm and unsorted aggregates < 8 mm (of which 60 % were < 2 mm diameter).

Dry matter yields are shown in the Table 3.13. Plants grown in plots comprising aggregates 4 - 8/ 2 - 4 mm diameter tended to have a lower dry weight at tillering than plants on other plots (difference significant only at $P = 0.10$). Table 3.13 indicates that dry matter production and grain production was higher in plots comprising unsorted aggregates treated without P.V.A. than when soil was treated with P.V.A.

As the data in Table 3.14 show, the treatments had little effect on root growth either at the time of emergence or at tillering.

The concentration of N in plant tops at tillering was significantly lower ($P = 0.05$) in plants from plots with aggregates 4 - 8/2 - 4 mm in diameter than in plants from other plots. The concentration of N in plant tops from plots made of aggregates not treated with P.V.A. is higher (but not always significant) than in plant tops from plots made of aggregates treated with P.V.A. The total N content in plant tops at tillering follows the same trend as the concentration of N. However total N content in plants from plots comprising unsorted aggregates (< 8 mm) was unaffected by P.V.A. treatment.

The concentration of N in straw from plots made of unsorted aggregates < 8 mm was significantly higher ($P = 0.05$) than the concentration of N in straw from other plots. However, concentration of N in grain was not significantly affected by aggregate size or P.V.A. treatments. The concentration of N in plant tops at harvest (i.e. concentration of N in grain + concentration of N in straw), from plots made of aggregates 2 - 4/< 2 and unsorted aggregates < 8 mm diameter is significantly higher than in plant tops from other plots. Total N in straw and total N in grain was the highest in plots made of aggregates 2 - 4/2 mm and in plots

TABLE 3.11. Germination emergence and survival of wheat as affected by soil aggregate size and P.V.A. treatment.

Aggregate size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		Unsorted < 8		L.S.D. P=0.05
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2	
Germination (%)	92.0	95.0	96.0	96.5	95.0	97.5	94.0	95.5	3.2
Emergence (%)	90.3	92.8	90.5	91.5	88.8	90.5	90.3	88.8	5.5
% plant per plot at tillering	91.5	93.3	87.3	92.3	86.8	88.5	85.5	88.0	2.6
% plant per plot at harvest	87.5	87.9	88.3	87.1	90.2	84.4	87.1	84.0	3.3

Footnote: The discrepancy in plant numbers is due to the fact that different plots were sampled at different times.

TABLE 3.12. Effect of aggregate size and P.V.A. treatment on mean day of emergence.

Aggregate size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		Unsorted < 8	
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2
Mean day of emergence	11.3	11.1	11.3	11.1	10.5	10.8	10.2	10.7

L.S.D. (P = 0.05) = 0.3

TABLE 3.13. Effect of aggregate size and P.V.A. treatments on total dry matter production of wheat at tillering (17 September) and straw and grain yields at harvest (5 December).

Aggregate size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		Unsorted < 8		L.S.D. P=0.05
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2	
Dry matter at tillering (g m^{-2})	91.2	75.2	104.8	102.0	114.4	103.2	110.8	100.8	31.8
straw (g m^{-2})	427.0	398.8	445.2	349.6	508.0	460.8	520.0	411.2	90.8
grain (g m^{-2})	326.0	282.4	322.8	249.2	357.2	341.2	347.2	312.0	64.4

TABLE 3.14. Effect of aggregate size and P.V.A. treatment on seminal root length and diameter at emergence (27 July) and total root length at tillering (17 September).

Aggregate size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		Unsorted < 8		L.S.D. P=0.05
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2	

Root diameter and root length measurements

Seminal root length mm/plant	53.8	53.4	45.3	50.0	50.1	44.3	43.6	47.5	15.0
Seminal axes diam. (mm)	0.63	0.58	0.59	0.57	0.62	0.56	0.56	0.54	0.18
Root length at 0-20 cm depth (cm g^{-1})	7.7	8.4	8.4	6.3	6.2	7.0	8.6	7.0	3.4
Root length at 20-40 cm depth (cm g^{-1})	6.2	5.6	6.2	6.2	5.6	6.2	5.9	5.9	3.0
Root length at 40-60 cm depth (cm g^{-1})	2.7	2.8	3.1	2.8	2.5	2.2	2.3	2.9	0.70

TABLE 3.15. Nitrogen concentration and total nitrogen in tops of wheat plants at tillering (17 September) and maturity (5 December).

Aggregate size (mm)	$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		Unsorted < 8		L.S.D. P=0.05
P.V.A. (%)	0	0.2	0	0.2	0	0.2	0	0.2	
N conc. in tillers (%)	2.64	2.49	3.39	2.69	3.08	2.77	2.97	2.71	0.23
Total N in tillers ($g\ m^{-2}$)	2.32	2.12	3.16	2.70	3.16	3.04	3.00	3.00	0.76
N conc. in straw (%)	0.57	0.55	0.62	0.59	0.69	0.66	0.84	0.74	0.11
N conc. in grain (%)	2.19	2.19	2.26	2.30	2.52	2.29	2.53	2.36	0.83
N conc. in straw + N conc. in grain (%)	1.27	1.23	1.30	1.30	1.43	1.38	1.51	1.39	0.10
Total N in straw ($g\ m^{-2}$)	2.39	2.20	2.75	2.41	3.66	3.09	4.42	2.69	0.84
Total N in grain ($g\ m^{-2}$)	7.33	6.23	7.30	5.74	8.73	8.18	8.81	7.38	1.94
Total N in straw + total N in grain ($g\ m^{-2}$)	9.72	8.43	10.05	8.15	12.39	11.27	13.23	10.07	2.16

made of unsorted aggregates < 8 mm the total N content in plant tops at maturity follows the same trend as the concentration of N (Table 3.15).

3.3.3.2 Discussion

During the period of germination to emergence (14 to 19 July), soil water in all plots was always below or slightly above field capacity, which for this soil is 18 % (Table 3.9). Consequently the air space was always higher than the minimum volume of air space of 10 to 15 percent regarded as satisfactory for germination (McIntyre 1955; Baver 1956). The soil water potential during the germination period was between -12 and -65 kPa which is substantially higher than the limit of -280 kPa considered to reduce germination (Williams and Shaykewich 1971; Pawloski and Shaykewich 1972; Ashraf and Abu Shakra 1978). Read and Beaton (1963) found that variation of temperature between 6 and 27°C did not affect the total germination of wheat but the optimum temperature for germination was between 16 and 26°C (61 and 80°F). In the experiment reported here the mean soil temperatures measured at 4cm depth between sowing and germination fell well within this range (maximum temperature 12.1°C and minimum 10.8°C) as shown in Table 3.7. Thus it was unlikely that temperature would have affected the total number of seeds of wheat germinated.

Plants were found to emerge earlier in plots made of smaller aggregates (2 - 4/< 2 mm) and unsorted aggregates than in plots made of larger aggregates (4 - 8/2 - 4mm and 4 - 8/< 2 mm). The results agree with those of Edwards (1957a) who found that emergence of barley and oats was earlier from aggregates 3 - 6 mm in diameter than for larger aggregates. Taylor (1974) obtained similar results for maize and sorghum. He found that maize and sorghum emerged earlier from seed-beds with aggregates < 2 mm in diameter. Thow (1963) found that, on clay soil, plants emerged earlier on plots with aggregates 0.76 - 6.35 mm diameter than on plots with coarser aggregates. According to Taylor (1974) seed-beds made of coarse aggregates can delay emergence by delaying germination because the contact area of the seed with wet soil is small. The time of seed-wet soil contact in these seed-beds may be shorter if coarse seed-beds lose water by evaporation more rapidly than finer seed-beds and this may in part explain the earlier emergence in finer seed-beds than in coarser seed-beds in the experiment reported here.

The penetrometer resistance measurements were inconsistent with the MDE. Plants emerged earlier from plots with unsorted aggregates (< 8 mm diameter) presumably because of better seed-soil contact, yet these plots had higher penetrometer resistance than all other plots. However, it must be remembered that penetrometer readings were made at the end of the emergence period and values of penetrometer resistances obtained were below those reported to affect emergence, so it is not surprising that MDE was not related to penetrometer resistance. Final emergence was not affected by aggregate size or P.V.A. treatment (Table 3.11). This is understandable as water potential and temperature in all the plots were not limiting factors for plant emergence. Water potential was similar in all the plots between germination and emergence (19 July, 25 July) and was favourable for wheat emergence (Hanks and Thorp 1957). The temperature also was similar in all the plots (Table 3.7) and in the range found to be favourable for wheat emergence (Wilson 1928; Singh and Dhaliwal 1972). Hanks and Thorp (1957) found that the limiting soil surface strength as measured by the modulus of rupture, for wheat emergence was 50 kPa (500 millibars). Braunack (1979) found that soil surface strength of 53 kPa, as measured with a hand penetrometer, did not limit wheat emergence. Soil surface strnegth as measured with a penetrometer in the current experiment was well below the values found by the above authors (Table 3.6). Hence it is unlikely that soil surface strength was a limiting factor in the total emergence of wheat plants.

Plots comprising aggregates 4 - 8/2 - 4 mm in diameter had lowest dry matter production of all treatments despite the fact that the number of plants per plot was the highest in these plots. Greater dry matter weight at harvest was obtained from the plots made of aggregates 2 - 4/< 2 mm diameter. These results agree with those obtained by Braunack (1979). A possible explanation to the fact that plants from plots made of aggregates 2 - 4/< 2 mm gave a higher yield than plants from plots made of aggregates 4 - 8/2 - 4 and 4 - 8/2 - 4 may be due to the possibility that more water could have been available to the plants in the former plots as smaller 2 - 4 mm size range cause minimum evaporative water loss (Hillel and Hadas 1972; Hadas 1975; Braunack 1979).

Treatments had no effect on accessibility of water or nutrients in so far as these are controlled by root distribution, which was similar in all plots (Table 3.14).

One factor which may have had an important bearing on final yields was nitrogen. The plants with the highest concentration of nitrogen were those which produced the highest yield at maturity (Yield of grain + yield of straw). The difference in nitrogen intake by the plants could be due to differences in amounts of nitrogen available in the soil. The rate of nitrogen transformations in the soil may have been affected by differences of environment in different plots. Movement of nitrogen in the soil may have been influenced by the differences in water percolation rates which is related to the porosity of different seed-beds.

On the soil used and under the conditions described, plants had a relatively better performance when grown in seedbeds made of small aggregates (< 4 mm) than larger aggregates (> 4 mm). Seed-beds layering did not seem to have affected plant performance as stratified seed-beds 2 - 4/< 2 mm and unstratified seed-beds < 8 mm (comprising 60 % of aggregates < 2 mm) gave similar results as far as state of plant emergence, dry matter and grain yield are concerned. Concentration of nitrogen and total nitrogen in the plants are similar for both seed-beds. Seed-beds with a top layer comprising aggregates 4 - 8 mm diameter gave a lower dry matter (straw) and grain yield than finer seed-beds. In the early stages of plant growth (emergence to tillering) seed-beds 4 - 8/2 - 4 mm had the lowest production of dry matter and the concentration and total nitrogen in the plants from these plots were the lowest.

SECTION 4. GLASS-HOUSE AND LABORATORY EXPERIMENTS

4.1 LEACHING AND MINERALISATION OF NITROGEN

4.1.1 Introduction

The results of the field experiment described in the Section 3 showed that wheat plants grown in stratified seed-beds made of graded aggregates (2 - 4/< 2 mm in diameter) and unsorted aggregates (< 8 mm in diameter) had a greater total N content than plants grown in seed-beds made of aggregates 4 - 8/2 - 4 mm or 4 - 8/< 2 mm in diameter. The difference in N content was greater when aggregates were not treated with P.V.A. A number of factors may have contributed to this result, such as the loss of N by leaching or denitrification or differences in the rate of mineralisation of N in the different seed-beds. Although loss of N by denitrification cannot be entirely discounted, it seems unlikely that denitrification would have been an important mechanism of loss in this case. Previous work on this soil by Stefanson and Greenland (1970), Burford and Greenland (1970), Stefanson (1972a,b; 1973b) and Burford and Stefanson (1973) has shown that gaseous losses are low from freely-drained sites. Moreover, in the field experiment described in the Section 3, those treatments which produced plants with the lowest nitrogen contents were not those likely to favour denitrification.

In order to test the hypothesis that the size and stability of aggregates may influence mineralisation and leaching of N, the following investigations were undertaken:

(a) Leaching experiment. The objective of this study was to determine the relationship between the movement of mineral N and the size and stability of soil aggregates under different water regimes.

(b) Incubation experiment. The net mineralisation of N in soil comprising different sized aggregates maintained under various conditions of temperature and water was examined.

The soil used in the study was collected from the same site as the field experiment. The procedures used for drying, sieving and treatment of the soil with P.V.A. were the same as described previously (Section 3).

4.1.2 Materials and methods

4.1.2.1 Leaching experiment

The experiment had a randomised block design with four replicates. The treatments arranged in a factorial combination were

Stratified seed-beds	4 - 8/2 - 4 mm diameter
	4 - 8/< 2 mm diameter
	2 - 4/< 2 mm diameter
P.V.A.	0 %, 0.2 %
Water (weekly addition)	75 ml x 1
	75 ml x 2
	150 ml x 1
	150 ml x 2

The stratified seed-beds comprising two layers of different sized aggregates each 4 cm deep, were contained in vertical P.V.C. tubes 7 cm in diameter and 30 cm long. The seed-beds were underlain by undisturbed cores of subsoil (10 cm A_2 and 10 cm B_1 horizon) taken from the site of the field experiment.

Cores of wet sub-soil were collected in a steel tube inserted with a hydraulic ram (Plate 13), and were coated with vinylidene polymer plastic 'Saran' to prevent disintegration. The cores were air dried and trimmed to 20 cm in length (1600 g). They were installed in the P.V.C. leaching tubes and retained at the base by performated P.V.C. plates. The cores were re-wet by placing the base of the tubes in water for a period of six days. Swelling of the soil during re-wetting ensured a tight fit of soil in the tube. The two layers of aggregates were then

PLATE 13. Collecting of soil cores in steel tubes with a hydraulic ram.

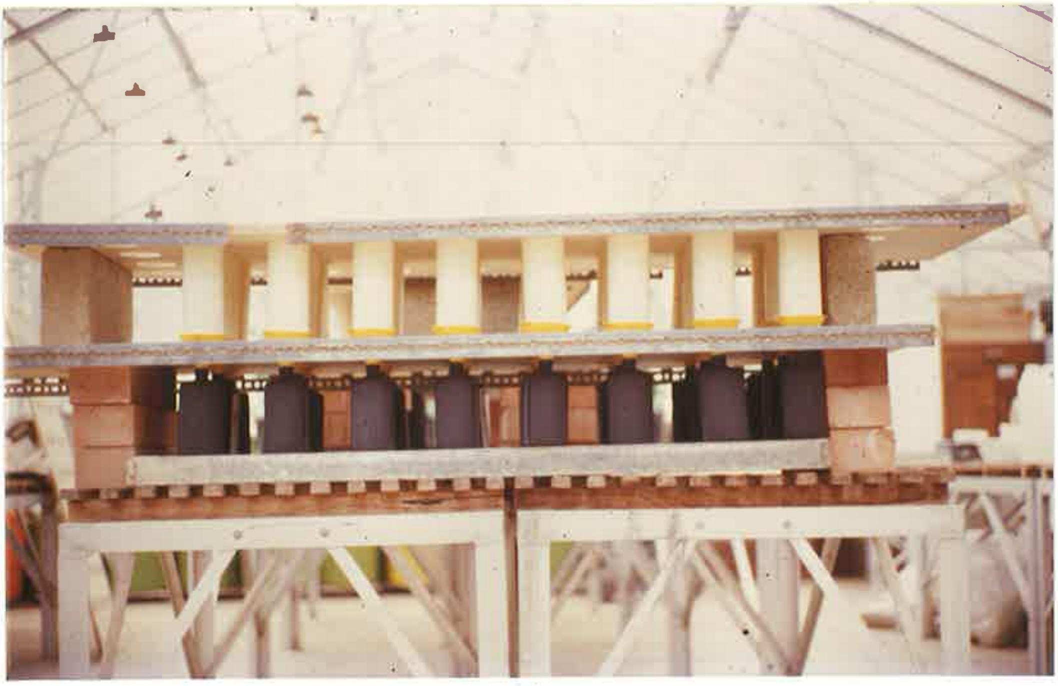

PLATE 14. Set up of the leaching experiment in the glass house.

added, each being wet to 18 % water content (field capacity) by a fine mist spray.

Nitrogen fertilizer (0.45 g as ammonium sulphate) was included in the water added to the lower layer of aggregates. The arrangement of the tubes is shown in Plate 14.

The leaching was done with rain water added at an intensity of 48 mm (± 0.1) h^{-1} once or twice weekly over a period of four weeks. The volume of leachate was measured at the end of each week and sub-samples were analysed for nitrate and ammonium content by the automated alkaline phenate method described by Keay and Menage (1970).

4.1.2.2 Incubation experiment

The experiment involved a split-plot design as follows:

Main plots:	Temperature (12/12 hours):	$5^\circ/10^\circ C$ and $12/24^\circ C$
Sub-plots:	Soil water content:	12 %, 24 %
	Aggregate size:	< 2 mm, 2 - 4 mm, 4 - 8 mm in diameter
	P.V.A.:	0 %, 0.2 %

Treatments within the main plots were arranged in factorial combination and replicated four times.

The aggregates (200 g) at the appropriate water content were incubated for up to six weeks in 500 ml jars covered with polyethylene film (25 μm thick) to reduce loss of water. The jars were weighed at intervals and any weight loss made up by addition of de-ionised water. The mineral nitrogen was extracted from 20 g sub-samples of the soil by shaking with 200 ml 2 N KCl for 2 hours. The suspensions were filtered and stored at $4^\circ C$ with a bactericide (phenyl mercuric acetate) added to prevent changes during storage. Mineral N (ammonium and nitrate) in the extracts was determined by the automated alkaline phenate method described by Keay and Menage (1970).

4.1.3 Results

4.1.3.1 Leaching experiment

(a) Movement of water and evaporation

As expected, the amount of water which percolated through columns of soil was closely related to the amount of water added (Table 4.1). The frequency of application of water had little effect on the amount of water which percolated through the columns. In the first two weeks, slightly but significantly greater ($P = 0.05$) amounts of water percolated through columns with twice-weekly application of 75 ml of water compared to a single weekly application of 150 ml. The converse occurred in the fourth week.

Table 4.2 shows that the percolation of water through soil columns with layers of different sized aggregates was unaffected by the size of the aggregates. In the first two weeks, percolation was also unaffected by treatment of the soil with P.V.A. However in the subsequent two weeks, the amount of water which percolated through columns with aggregates treated with P.V.A. was significantly higher ($P = 0.05$) than the amount of water collected from columns where the aggregates were not so treated.

The total amount of water which percolated through the soil columns during the four weeks of the experiment is given in Table 4.3. While the greatest differences were brought about by the quantity of water applied, it is also clear that the downward movement of water through soil columns was enhanced by the treatment of the aggregates with P.V.A. In general, aggregate size had little effect on the percolation. The interactions between the water treatments and aggregate size and P.V.A. treatments were not significant at $P = 0.05$. It follows that evaporation of water from the surface of the soil in the tubes was affected by the treatments in a manner converse to percolation, as the soil columns were at field capacity before and after the application of water.

(b) Nitrogen leached

The initial concentrations of (NH_4)-N and (NO_3)-N in the aggregates used for the leaching and incubation experiments are shown in Table 4.5. All aggregates had similar contents of total mineral N [50 ± 2ppm (NO_3+NH_4)-N]. But those treated with P.V.A. had a slightly higher (NH_4)-N and slightly lower (NO_3)-N content than the untreated aggregates. In the undisturbed cores of soil, nitrate contents were low in both the A_2 and B_1 horizons (4.8 and 3.7 p.p.m. (NO_3)-N respectively) and there were only traces of (NH_4)-N.

The concentration of (NH_4)-N and (NO_3)-N in the leachates were similar (Table 4.6). As might be expected, the concentrations decreased with time and they were inversely proportional to the amount of water added. The frequency of water application also significantly affected the concentration of the leachate (Table 4.6). In the first and second week, the concentration of (NH_4)-N in the leachates was not affected by the frequency of watering, but in the third and fourth weeks, concentration of (NH_4)-N was significantly higher when the water was added twice weekly than when water was added once weekly. The concentrations of (NO_3)-N in the leachate followed a pattern similar to that of (NH_4)-N.

Table 4.7 shows that the concentrations of (NH_4)-N and (NO_3)-N in leachates from columns with different sized aggregates either treated or not treated with P.V.A. In the first week, the concentrations of (NH_4)-N were significantly higher in leachates from columns with aggregates 4 - 8/2 - 4 mm in diameter treated with P.V.A. than in all other treatments. However, the concentration of (NO_3)-N was not affected by aggregate size. The concentrations of (NO_3)-N in leachates from columns with aggregates 4 - 8/< 2 mm and 2 - 4/< 2 mm in diameter, were significantly higher $(P = 0.05)$ when the aggregates were treated with P.V.A. than when the aggregates were not treated with P.V.A. In the second week, concentration of (NH_4)-N in leachates was not affected by aggregate size or P.V.A. treatment. The same applies for (NO_3)-N. In the third week, concentrations of (NO_3)-N and (NH_4)-N were significantly higher ($P = 0.05$) in leachates from columns with aggregates 4 - 2/< 2 mm and 2 - 4/< 2 mm in diameter than in leachates from columns with aggregates 4 - 8/2 - 4 mm diameter. The same pattern occurred in the fourth week except for aggregates 2 - 4/< 2 mm. In the fourth week, the concentrations of (NO_3)-N and (NH_4)-N in the leachates was significantly higher when the aggregates were not treated with P.V.A. than when they were, except for the treatment 2 - 4/< 2 mm diameter.

It follows from the results presented in Table 4.8, that the amount of (NH_4)-N leached increased as the quantity of water added increased, and that most of (NH_4)-N was removed in the first two weeks of leaching. The frequency of application of water had only small effects on the amount of (NH_4)-N leached, but it was evident in the later weeks that slightly more N was removed by the more frequent application of water. As with (NH_4)-N, more than half of the (NO_3)-N was removed during the first week and the quantity of (NO_3)-N in the leachate was also proportional to the amount of water added. In the subsequent three weeks, the amount of (NO_3)-N leached was slightly but significantly higher ($P = 0.05$) when water was added in twice weekly applications than when it was added in a single weekly application.

The amounts of (NH_4)-N and (NO_3)-N leached from columns with different sized surface aggregates are shown in the Table 4.9. In the first week, more of the (NH_4)-N was leached from seed-beds with aggregates treated with P.V.A. irrespective of the size of the aggregates. In the subsequent two weeks, there was no significant difference ($P = 0.05$) of amounts of (NH_4)-N leached, between different treatments, but, in the fourth week, a significantly higher ($P = 0.05$) amounts of (NH_4)-N was found in leachates from columns with aggregate not treated with P.V.A.

TABLE 4.1. Percolation of water through soil columns in relation to the quantity and frequency of water applied.

Water applied per week (ml)		75 x 1	75 x 2	150 x 1	150 x 2	L.S.D. (P=0.05)
Percolation (ml)	week 1	49	121	109	226	2.1
	week 2	51	120	115	250	3.5
	week 3	47	109	107	239	3.7
	week 4	39	100	112	246	2.6

(Table based on separate analyses of variance for each week)

TABLE 4.2. Percolation of water through soil columns with surface layers of different sized aggregates as affected by treatment with P.V.A.

Aggregate size (mm)		$\frac{4-8}{2-4}$		$\frac{4-8}{<2}$		$\frac{2-4}{<2}$		L.S.D. (P=0.05)
P.V.A. (%)		0	0.2	0	0.2	0	0.2	
Percolation (ml)	week 1	131	143	132	135	128	132	5.2
	week 2	132	138	130	138	130	137	(8.6)
	week 3	118	135	121	131	119	130	9.0
	week 4	121	131	120	130	119	126	6.4

(Table based on separate analyses of variance for each week)

TABLE 4.3. Total percolation of water through soil columns as affected by aggregate size, P.V.A. treatment and the quantity and frequency of water application.

Aggregate size (mm)		$\frac{4-8}{2-4}$		$\frac{4-8}{<2}$		$\frac{2-4}{<2}$	
P.V.A. (%)		0	0.2	0	0.2	0	0.2
		Water percolated (ml)					
Water applied (ml/week)	75 x 1	172	212	168	206	167	183
	72 x 2	441	466	439	471	422	462
	150 x 1	434	481	427	462	417	437
	150 x 2	962	1032	962	996	977	1006

Interaction L.S.D. (P = 0.05) = 29.0

TABLE 4.4. Summary of the analysis of variance for total amounts of water percolated during the four week period.

	D.F.	M.S.	V.R.
Agg.	2	1923.8	4.42 *
P.V.A.	1	29190.4	67.01 ***
Wat.	3	2764332.2	6345.43 ***
Agg. X P.V.A.	2	715.7	1.64 N.S.
Agg. X Wat.	6	439.8	1.01 N.S.
P.V.A. X Wat.	3	159.3	0.37 N.S.
Agg. X P.V.A. X Wat.	6	444.9	1.02 N.S.
Residual	69	435.6	

•

TABLE 4.5. Mineral nitrogen content in different sized aggregates before leaching and incubation experiments.

Agg. size (mm)	4-8		2-4		< 2		L.S.D. (P=0.05)
P.V.A. (%)	0	0.2	0	0.2	0	0.2	
NH_4-N (ppm)	22.0	24.9	20.7	24.2	21.3	21.5	4.1
NO_3-N (ppm)	29.3	26.9	29.0	26.4	28.7	25.5	7.3

TABLE 4.6. Concentration of (NH_4)-N and (NO_3)-N in leachates from soil columns, in relation to the volume of water applied.

Water applied (ml)		75 x 1	75 x 2	150 x 1	150 x 2	L.S.D. (P=0.05)
(NH_4)-N (ppm)	week 1	505	328	366	200	64.5
	week 2	262	183	159	100	31.8
	week 3	40	30	24	16	4.6
	week 4	23	21	15	10	3.2
(NO_3)-N (ppm)	week 1	437	336	384	173	98.0
	week 2	171	146	119	63	28.4
	week 3	30	28	21	9	4.8
	week 4	30	24	16	5	4.8

(Table based on separate analyses of variance for each week)

TABLE 4.7. Concentration of (NH_4)-N, (NO_3)-N in leachates from soil columns with layers of different sized aggregates, treated and not treated with P.V.A.

Aggregate size (mm)		$\frac{4-8}{2-4}$		$\frac{4-8}{<2}$		$\frac{2-4}{<2}$		L.S.D. (P=0.05)
P.V.A. (%)		0	0.2	0	0.2	0	0.2	
(NH_4)-N (ppm)	week 1	217	720	267	266	266	365	80.0
	week 2	158	144	190	181	162	204	39.0
	week 3	20	21	35	29	32	26	6.0
	week 4	15	11	24	15	23	16	4.0
(NO_3)-N (ppm)	week 1	203	315	261	467	209	366	120.0
	week 2	102	102	143	132	124	147	34.8
	week 3	18	11	28	21	29	26	6.0
	week 4	19	12	26	18	22	17	6.0

(Table based on separate analyses of variance for each week)

TABLE 4.8. Amounts of (NH_4)-N and (NO_3)-N leached from soils columns, in relation to the volume of water applied.

Water applied (ml)		75 x 1	75 x 2	150 x 1	150 x 2	L.S.D. (P=0.05)
(NH_4)-N (mg)	week 1	25	40	41	52	7.0
	week 2	12.9	21.8	18.2	24.7	3.9
	week 3	1.9	3.2	2.5	3.7	0.36
	week 4	0.8	2.1	1.7	2.3	0.26
(NO_3)-N (mg)	week 1	21	41	42	50	11.0
	week 2	8.7	17.5	13.7	16.1	3.8
	week 3	1.4	3.1	2.2	2.2	0.46
	week 4	1.1	2.4	1.7	1.3	0.48

TABLE 4.9. Amounts of (NH_4)-N and (NO_3)-N leached from soil columns containing different sized aggregates treated or not treated with P.V.A.

Aggregate size (mm)		$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$		L.S.D. (P=0.05)
P.V.A. (%)		0	0.2	0	0.2	0	0.2	
(NH_4)-N (mg)	week 1	27	84	29	31	25	40	8.7
	week 2	18	17	20	20	19	22	2.8
	week 3	2.3	2.3	3.5	3.1	3.0	2.9	0.4
	week 4	1.7	1.2	2.2	1.5	2.1	1.6	0.2
(NO_3)-N (mg)	week 1	24	67	27	53	19	41	13.4
	week 2	12	12	15	14	15	16	2.3
	week 3	2.0	1.0	2.8	2.8	2.8	2.6	0.2
	week 4	1.7	1.0	2.3	1.5	1.8	1.5	0.2

TABLE 4.10. Total amounts of $(NO_3 + NH_4)$-N leached from soil columns as affected by aggregate size, P.V.A. treatment and quantity and frequency of water application.

Aggregate size (mm)		$\frac{4-8}{2-4}$		$\frac{4-8}{< 2}$		$\frac{2-4}{< 2}$	
P.V.A. (%)		0	0.2	0	0.2	0	0.2
		$(NH_4 + NO_3)$-N (mg)					
Water appl. (ml per week)	75 x 1	41	114	69	89	52	77
	75 x 2	100	208	100	140	98	144
	150 x 1	87	202	102	120	95	129
	150 x 2	127	217	140	155	107	163

Interaction L.S.D. $(P = 0.05) = 43$

TABLE 4.11. Total amounts of mineral nitrogen leached. Summary of the analysis of variance for the total four week period.

	Total amount of $(NH_4 + NO_3)$-N leached		
	D.F.	M.S.	V.R.
Agg.	2	7344.5	8.01 ***
P.V.A.	1	68352.9	74.50 ***
Wat.	3	26253.1	28.61 ***
Agg. X P.V.A.	2	11837.0	12.90 ***
Agg. X Wat.	6	611.7	0.67 N.S.
P.V.A. X Wat.	3	673.7	0.73 N.S.
Agg. X P.V.A. X Wat.	6	338.0	0.37 N.S.
Residual	69	917.5	

than in leachates from columns with aggregates treated with P.V.A., irrespective of the size of the aggregates. The amounts of (NO_3)-N leached followed the same trend as (NH_4)-N.

Table 4.10 indicates the amounts of mineral N leached was not affected by aggregate size at any time. However, treatment of aggregates with P.V.A. permitted greater leaching of mineral N of up to 100 % more for particularly larger aggregates and up to 25 % more for smaller aggregates.

4.1.3.2 Incubation experiment

The mineral N contents of the soils are shown in Tables 4.12 and 4.14. There were slight increases in (NH_4)-N and substantial increases in (NO_3)-N during the first week's incubation, but the effect of the treatments was relatively small. There was a tendency for (NH_4)-N to be slightly higher and (NO_3)-N slightly lower where P.V.A. was applied, but many of the differences were not significant at $P = 0.05$ and they essentially disappeared during the subsequent five weeks' incubation (Table 4.12). During this time, the (NH_4)-N contents of the soil declined, while there were substantial increases in (NO_3)-N.

Aggregate size had little effect on net mineralisation of N, but the environmental conditions did have a significant influence (Table 4.13). During the first week, the amount of (NH_4)-N produced was higher at 12/24°C than at 5/10°C. After six weeks incubation, production of (NH_4)-N was not affected by temperature; however (NH_4)-N was significantly higher $(P = 0.05)$ at 24 % water content than at 12 % water content when temperature was 12/24 or 5/10°C. (NO_3)-N follows the same trend.

During the first week, production of (NO_3)-N was significantly higher $(P = 0.05)$ at 24 % water content than at 12 % water content when the temperature is 5/10°C (Table 4.13). Total mineral N was significantly higher $(P = 0.05)$ at 24 % water content than at 12 % water content for

TABLE 4.12. Mineral N content of soil after incubation of different sized aggregates treated with P.V.A.

Aggregate size (mm)	4-8		2-4		< 2		L.S.D. (P=0.05)
P.V.A. (%)	0	0.2	0	0.2	0	0.2	
(NH_4)-N (ppm) After 1 week incub.	25.4	26.1	22.4	29.0	23.0	28.3	1.8
(NH_4)-N (ppm) After 6 weeks incub.	19.2	18.7	19.0	17.9	18.3	18.4	3.4
(NO_3)-N (ppm) After 1 week incub.	51.7	48.6	47.9	45.7	49.6	43.1	5.8
(NO_3)-N (ppm) After 6 weeks incub.	80.3	82.6	77.8	80.0	81.8	80.6	9.0

TABLE 4.13. Mineral N content of soil as affected by the temperature and water content of the soil during incubation.

Temperature (^{o}C)	5/10		12/24		L.S.D. (P=0.05)
Water content (%)	12	24	12	24	
(NH_4)-N (ppm) After 1 week incub.	19.4	25.1	26.4	31.9	1.5
(NH_4)-N (ppm) After 6 weeks incub.	16.9	20.4	17.5	19.6	2.0
(NO_3)-N (ppm) After 1 week incub.	41.4	51.6	49.7	48.3	8.3
(NO_3)-N (ppm) After 6 weeks incub.	75.0	88.8	66.1	92.1	6.6

TABLE 4.14. Effect of temperature, P.V.A. treatments and aggregate sizes on net mineralisation of nitrogen in Urrbrae red-brown earth during six weeks incubation.

Aggregate size (mm)	4-8		2-4		< 2		L.S.D. (P=0.05)
P.V.A. (%)	0	0.2	0	0.2	0	0.2	
			$(NH_4 + NO_3)$-N (ppm)				
Temperature (°)							
5/10	50.5	53.7	47.3	49.0	48.4	52.2	
12/24	45.9	43.4	46.8	43.7	52.0	51.8	10.8
Water (%)							
12	39.5	40.9	38.8	39.9	34.9	40.6	
24	56.8	56.2	55.3	52.8	65.5	63.4	10.8

TABLE 4.15. Net mineralisation of nitrogen after six weeks incubation. Summary of the analysis of variance.

	Net mineralisation of nitrogen		
	D.F.	M.S.	V.R.
Wat.	1	12344.8	105.60 ***
Agg.	2	78.3	0.67 N.S.
P.V.A.	1	7.7	0.07 N.S.
Temp. X Wat.	1	717.0	6.13 *
Temp. X Agg.	2	161.0	1.38 N.S.
Wat. X Agg.	2	427.5	3.66 N.S.
Temp. X P.V.A.	1	139.6	1.20 N.S.
Wat. X P.V.A.	1	296.5	2.54 N.S.
Agg. X P.V.A.	2	19.5	0.17 N.S.
Temp. X Wat. X Agg.	2	350.0	2.99 N.S.
Temp. X Wat. X P.V.A.	1	93.1	0.80 N.S.
Temp. X Agg. X P.V.A.	2	1.3	0.01 N.S.
Wat. X Agg. X P.V.A.	2	31.5	0.27 N.S.
Temp. X Wat. X Agg. X P.V.A.	2	49.0	0.42 N.S.
Residual	66	116.9	

temperatures of $5/10^{\circ}$C.

The effects of the treatments on net mineralisation over the six week incubation period are summarised in Table 4.14. Aggregate size and P.V.A. treatment had no effect, but there was significantly more ($P = 0.05$) total mineral N produced in aggregates with high water content (24 %) compared to aggregates with low water content (12 %).

4.1.4 Discussion

4.1.4.1 Leaching experiment

There were only small differences in the amounts of water which percolated through soil columns with layers of different sized aggregates. However, in the last two weeks of the experiment, the quantity of water which percolated through soil columns containing aggregates treated with P.V.A. was significantly higher ($P = 0.05$) than where the aggregates were not treated with P.V.A. (Table 4.3). This can be attributed to the fact that aggregates treated with P.V.A. were more stable and were broken down by application of water to a lesser extent than untreated aggregates (the inter-aggregate pores at the surface of the soil were filled to a lesser extent with micro-aggregates when the aggregates were treated with P.V.A., leading to more free percolation of water in these columns). Although no measurements of soil structure were made in this experiment, aggregates treated with P.V.A. clearly maintained their shape throughout the experiment. Aggregates not greated with P.V.A. started to disintegrate from the initial watering and after the first two weeks of the experiment, the surface of the soil in the tubes had formed a crust which clearly restricted the rate of infiltration of water and permitted greater evaporation. Measurements of soil structure described in Section 3, confirm the observations made here, i.e. beds of aggregates treated with P.V.A. maintained a larger macro-porosity, at the soil surface, than when the aggregates were not treated with P.V.A.

Aggregate size had little effect on evaporation of water. This confirms the results of Hillel and Hadas (1972) who found that under low evaporativity the aggregate size range 0.25 - 5 mm diameter has no effect upon cumulative water loss where the frequency of watering was equal to or less than 10 days as was the case in the present experiment. However, Hillel and Hadas (1972) found that under high evaporativity, soil aggregates of 0.5 - 1 mm had a lower cumulative evaporation than aggregates smaller than 0.5 mm and larger than 1 mm. Aggregates smaller 0.55 mm apparently allowed greater evaporation because of better water conductivity whereas larger aggregates allowed greater water loss possibly because of better penetration of turbulent air currents into the interaggregate cavities (Hanks and Woodruff 1958; Farrell *et al.* 1966). Braunack found that when water was unlimited, aggregates 2 - 4 mm size range had lower evaporation than larger aggregates (4 - 8 mm) or smaller aggregates (< 1 mm). In the field situation, loss of water would be less affected by aggregate size in winter when evaporation is low than during spring and summer, when aggregate size could play an important role in determining the rate of evaporative loss of water. Measurements of soil water potential presented in the Section 3 confirm that between 14 July and 25 July (germination to emergence), water potential of the soil was not greatly affected by aggregate size.

It is well known that leaching of N in the soil is closely related to the amount of water added (Bates and Tisdale 1957; Kolenbrander 1970). However leaching of N may also be affected by the frequency of water application (Thomas 1970). The effects of frequency of water application on leaching of N depend on factors such as soil properties, intensity of water application (or intensity of rainfall), and evaporation (Thomas, 1970; Kolenbrander 1970). In the experiment described here, the frequency of water application on leaching of N was not significant in the first two weeks of water application, but in the subsequent two significantly more N was removed when water was added in two applications per week than when water was added in one weekly application. A possible explanation to this is that when water was added in one application, and large pores are empty, water moves essentially through those large pores and removes the N in these large pores only. But when water is added in two applications, diffusion of N out of the micropores may occur between waterings, and may be leached in the second application of water. Similar results were found by Thomas (1970).

The greater amount of mineral N in leachates from soil columns with layers of different sized aggregates treated with P.V.A. could be explained by the greater downward movement of water in the columns (as explained above), as the movement of N is closely related to the quantity of percolated water.

A number of factors which were not studied here, particularly the absence or presence of plants and their associated micro-organisms, the type of plant and its root distribution characteristics would affect the movement of mineral N. The presence of plants, by removing mineral N from the soil and by restricting downward movement of water decreases leaching of N (Cunningham and Cooke 1958; Gasser 1959; Belan and Coppenet 1980; Long and Huck 1970).

In conclusion, it may be stated that while the present experiment provides no quantitative information on movement of N through the soil under a growing crop in the field, there is clear evidence that differential leaching of N can be brought about by treatment of soil aggregates with P.V.A. The frequency of water application also affected leaching of N, but size of aggregates had little effect.

4.1.4.2 Incubation experiment

The mineralisation of N in different sized aggregates maintained under various conditions of temperature and water showed that there was no significant difference ($P = 0.05$) in N mineralisation between different aggregate sizes after one week's and six weeks' incubation. These results are in substantial agreement with those obtained by Fitts (1953) who stated that soil aggregate size had little influence upon mineral N production. He found approximately the same nitrification rate in aggregates < 9.5, < 2 and 0.84 mm in diameter incubated at optimum water content (between 25 and 35 %) and temperature of 30°C. The same conclusion was reached by Hagin and Halevy (1961). However, Craswell *et al.* (1970) found that N mineralisation in anaerobic conditions, increased with decreasing aggregate size from > 5 mm to < 0.1 mm in diameter. They attributed this trend to the quantity and quality of readily mineralisable organic matter in the different aggregates. Aggregates < 1, 2 - 4, 4 - 8 mm diameter were found to have similar carbon content (Braunack 1979). Waring and Bremner (1964) found that in soil aggregates < 0.18 mm diameter, the amount of N mineralised under aerobic conditions at 30°C was significantly greater than that for aggregates < 2 mm diameter. Similar results were found by Seifert (1964). Both authors attributed this trend to differences in aeration of different sized aggregates. No significant difference ($P = 0.05$) in N mineralisation was observed between aggregates treated with P.V.A. and aggregates not treated with P.V.A. However, in the first week's incubation, (NH_4)-N had a tendency to be slightly greater and (NO_3)-N slightly lower when aggregates were treated with P.V.A. than when aggregates were not treated with P.V.A. These results are expected because according to Edwards and Bremner (1967) and Craswell *et al.* (1970), mineralisation of N in different sized aggregates from cultivated soil is independent of the strength of the aggregates.

The conditions of incubation (water and temperature) chosen in this investigation are similar to those found in the field during the period June to November. These conditions were chosen to get some idea of how much nitrogen was likely to be mineralised in the field. For this reason the results obtained in this study are not directly comparable with those obtained by other workers who usually use the standard favourable laboratory conditions (30°C and aerobic or anaerobic conditions). However, Hart *et al.* (1979) found that an increase of temperature from 17 to 24°C did not affect soil mineralisation in the presence or absence of plants in a pot experiment, because the rise of 7°C (from 17 to 24°C) may not have been high enough to cause any quantitative effect on soil microbial activity and inorganic N production. Similarly a variation of temperature from 5/10°C to 12/24°C did not affect mineralisation of N after six weeks incubation. In the case of the experiment described here, water content and temperature were controlled during the incubation.

Production of mineral N was significantly higher ($P = 0.05$) at higher water content (24 %). This is in agreement with the results obtained by Harmsen and Van Shreven (1955) and Hart *et al.* (1979) who found that increasing soil water content from 15 % to 30 % increased mineralisation of N.

Water content and temperature were controlled during the incubation experiment. In the field where these are not controlled, different water contents and temperatures may pertain with different sized aggregates and this could affect the rate of production of mineral N. Mineralisation of N in the field is also influenced by number of other factors which are not studied here. For example Goring and Clark (1948) found that accumulation of mineral N in soil under crop was considerably less than in corresponding fallow even though allowance was made for the N uptake by the growing crop. Similar results were found by Hart *et al.* (1979). This difference was attributed to the immobilization of N by the increased microbial population in cropped soil. The application of N fertilizer may also affect the mineralisation of organic soil N.

Broadbent (1965), for example, found that adding N had a stimulating effect on N mineralisation in the soil. This stimulating effect was attributed partly to the activity of rhizosphere microflora which increased when N fertilizer was added, and partly to osmotic effects of added fertilizer salts, in the absence of growing plants.

In conclusion, it may be stated that despite variation in environment, there was little effect of aggregate size and aggregate stability on net mineralisation in the field. It seems reasonable to assume therefore that mineralisation in the field is unlikely to have been greatly affected by aggregate size and P.V.A. treatments of this soil.

4.2 CRUST STRENGTH, WATER CONTENT, AND SEEDLING EMERGENCE

4.2.1 Introduction

Aggregate breakdown at the soil surface upon wetting can have adverse effects on infiltration of water and aeration in the soil. It causes crusting of the soil surface which can prevent seedling emergence if the crust is hard enough.

In the field experiment described in the Section 3, it was found that the rate of wheat emergence was affected by aggregate size and aggregate stability but ultimate emergence was similar in all the plots even though a crust was formed at the surface of the plots comprising soil aggregates untreated with P.V.A. The crust remained soft during the emergence period and was easily penetrated by the wheat seedlings. However, if a rapid drying of the soil had occurred after rain, the surface crust could have been strong enough to affect emergence seriously as is often the case with red-brown earths.

The aim of the glasshouse pot experiment described here was to determine the strength of the crusts formed on beds of different sized aggregates of Urrbrae loam treated or not treated with P.V.A. and to relate crust strength to the emergence of wheat seedlings. Crust strength was varied by varying the water content of the soil.

4.2.2 Materials and methods

The experiment was conducted in a glasshouse maintained at a constant temperature of 15°C ± 1. The experiment had a randomized block design with four replications. The treatments, which were arranged in a factorial combination, were

Aggregate size : 4 - 8, 2 - 4 and < 2 mm in diameter
P.V.A. : 0 % and 0.2 %
Water regime : wet, intermediate and dry

The soil used was from the same site as the field experiment and the preparation of the aggregates and P.V.A. treatments were done as described in Section 3. Pots, 14 cm in diameter and 15 cm high, were filled with two layers of soil. The lower layer (8 cm deep) was the same in all the pots, and consisted of unsorted soil < 8 mm in diameter. The top layer of the soil (4 cm deep) consisted of aggregates of one of the sizes listed above, treated or not treated with P.V.A. The total dry weight of soil in each pot was 1200 g. Ten wheat seeds were sown in each pot at 4 cm depth on 24 July. The water content of the soil was adjusted to 20 % by weight in all the pots by means of a mist spray applied at an intensity of 20 cm h^{-1}. No further water was added to the top layer of the soil in the pots. Different water regimes were produced by covering the soil in two sets of pots with a sheet of polytheme (25 μm thick), either immediately (wet regime) or three days after sowing (intermediate regime). The soil in the third set of pots (dry regime) was left uncovered.

When seedlings began to emerge (31 July), crust strength was measured with a pocket penetrometer (Soil test Model CL-700) fitted with a steel probe 6.35 mm in diameter with flat tip. Penetrometer measurements in each pot were replicated four times. At the same time, samples of crust were taken for the determination of gravimetric water content.

Emerging plants were counted daily, and mean day of emergence and total emergence were determined. Total dry matter yield was also measured when the plants were harvested on 10 August.

4.2.3 Results

Although there were the expected differences in the water content of the crust associated with the different water regimes, there was no significant difference ($P = 0.05$) in the water content of the crust from different pots maintained at the same water regime as shown in Table 4.16. The same table shows that maximum penetrometer resistance occurred with aggregates < 2 mm in diameter irrespective of the water content of the soil. As might be expected, penetrometer resistance increased with decreasing water content of the soil. Under the wet and intermediate water regime, P.V.A. treatment did not significantly affect penetrometer resistance. However, under the dry water regime, penetrometer resistance of the large (4 - 8 mm) aggregates was notably higher where they were treated with P.V.A. than where untreated.

The emergence of wheat seedlings was significantly earlier ($P = 0.05$) in the wetter than in the drier pots (Table 4.17). The intermediate and dry water regimes of aggregates 4 - 8 mm diameter treated with P.V.A. allowed the plants to emerge earlier than in pots with untreated aggregates. Table 4.17 shows that the maximum percentage emergence was obtained in pots with aggregates 4 - 8 and 2 - 4 mm diameter irrespective of the water regime.

In the wet pots, plant emergence was not affected by P.V.A. treatment of the soil, but with the intermediate water content of the soil, plant emergence was significantly higher in pots containing aggregates 4 - 8 mm treated with P.V.A. than in pots containing the same size range of aggregates untreated with P.V.A. The reverse occurred in

TABLE 4.16. Effect of aggregate size, P.V.A. treatment and water regime on the water content of the crust and penetrometer resistance of the soil.

Aggregate size (mm)		4-8		2-4		< 2		
P.V.A. (%)		0	0.2	0	0.2	0	0.2	
		Water Content of the Crust (%)						L.S.D. P=0.05
Water Regime	Wet	19.4	17.4	19.0	17.0	19.8	19.0	5.4
	Int.	7.6	8.9	12.5	11.2	10.2	9.0	
	Dry	2.2	2.0	3.2	3.0	3.2	3.0	
		Penetrometer resistance (kPa)						
Water Regime	Wet	20	21	21	20	44	51	10.4
	Int.	50	41	41	50	90	94	
	Dry	250	274	274	266	330	341	

TABLE 4.17. Effect of aggregate size, P.V.A. treatment and water regime, on mean day of emergence, total emergence, and dry matter production.

Aggregate size (mm)		4-8		2-4		< 2		
P.V.A. (%)		0	0.2	0	0.2	0	0.2	
		Mean day of emergence						L.S.D. P=0.05
Water Regime	Wet	8.4	8.7	7.8	8.5	8.4	8.3	0.59
	Int.	14.5	9.0	10.8	10.2	10.2	10.2	
	Dry	12.0	10.8	10.8	9.4	9.5	-	
		Total emergence (%)						
Water Regime	Wet	85	75	65	70	70	60	18.0
	Int.	20	90	70	80	50	30	
	Dry	50	65	45	20	10	0	
		Dry matter production (g/pot)						
Water Regime	Wet	0.14	0.16	0.13	0.16	0.15	0.13	0.02
	Int.	0.12	0.14	0.11	0.13	0.08	0.09	
	Dry	0.07	0.11	0.07	0.06	-	-	

pots containing aggregates < 2 mm diameter (Table 4.17). When the soil was dry significantly higher (P = 0.05) plants emerged in pots containing aggregates 2 - 4 mm diameter treated with P.V.A. than when untreated with P.V.A.. P.V.A. treatment did not affect plant emergence in pots containing aggregates 4 - 8 and < 2 mm diameter. Dry matter production decreased with decreasing water content of the soil as might be expected (Table 4.17). Aggregate size and P.V.A. treatment did not affect dry matter production.

4.2.4 Discussion

Results in Table 4.16 show that aggregates 4 - 8 mm diameter dry slightly more quickly than aggregates 2 - 4 mm or aggregates < 2 mm diameter although the differences were not significant at P < 0.05. Braunack (1979) found that loss of water through evaporation from Urrbrae loam was the highest for aggregates > 4 mm and the lowest for aggregates 2 - 4 mm diameter. Larger aggregates allow greater water loss through soil drying because of better penetration of turbulent air currents into the inter-aggregate cavities (Hanks and Woodruff 1965; Farrell *et al.* 1966; Hillel and Hadas 1972; Braunack 1979). Penetrometer resistance of the soil increased as the water content decreased. These results agree with those of Bennett *et al.* (1964); Lemos and Lutz (1957), Braunack (1979). P.V.A. treatment which was used to prevent crust formation by stabilizing the surface of the aggregates has an effect contrary to the one expected especially at dry water regime where the penetrometer resistance of the soil was higher when aggregates were treated with P.V.A. This may have been due to the fact that water content of the crust was slightly but not significantly higher when aggregates were not treated with P.V.A. than when aggregates were treated with P.V.A.. Hanks and Thorp (1957), Lemos and Lutz (1957), Braunack (1979) observed that the capacity of plants to penetrate the crust is related to crust water content.

It appears from the data in Tables 4.16 and 4.17 that a good relationship between seedling emergence and penetrometer resistance exists for aggregates < 2 mm in diameter, but overall the relationship between seedling emergence, penetrometer resistance and water content of the crust is not very clear.

A regression equation was developed to determine the relationship of penetrometer resistance P and water content C to total plant emergence EM.

$$EM = 23.91 - 0.0120P + 2.4361C$$

The equation shows that emergence is directly related to water content of the soil and inversely related to the penetrometer resistance, as might be expected. The percentage of variance for water content C and penetrometer resistance was 39.2 and 31.4 respectively. Hanks and Thorp (1956) found that crusts (as measured by the modulus of rupture) of 140 kPa inhibited emergence of wheat plants. This figure is below the values which diminished or inhibited wheat plant emergence in the current experiment. However it may not be valid to relate directly emergence to crust strength as the emergence force exerted by plants is controlled by factors such as temperature (Williams 1963; Jensen *et al.* 1972; Braunack 1979) and water status of the plants (Hadas and Stibbe 1977). In the current experiment, poor emergence in dry soil may have been due in part to crust strength and in part to the fact that the plants suffered from water shortage as reflected in the low dry matter yields (Table 4.16). Where plants are water stressed they are unable to exert their emergence force during emergence.

The MDE was related to penetrometer P resistance and soil water content C as follows

$$MDE = 12.97 - 0.0089P + 0.1947C$$

Surprisingly the effects of both water content of the crust C and penetrometer resistance P on MDE are small (percentage of variance accounted for = 14.2). MDE is more related to water content of the crust and marginally related to penetrometer resistance. In the case of this experiment rate of emergence may also have been influenced by the differential soil/seed contact in different treatments. Soil/seed contact was presumably the poorest in large aggregates especially those treated with P.V.A., hence a late emergence in this treatment (Table 4.17). It is also possible that emergence was delayed in the treatment 4 - 8 mm aggregate size range treated with P.V.A. because the plants were suffering water stress, as this size range of aggregates was found to dry more quickly than other treatments. This supports the results found by Hadas (1975) and Braunack (1979).

Dry matter (D.M.) production was related to the water content of the crust C and penetrometer resistance P as follows

$$\text{D.M.} = 0.124 - 0.0003P + 0.0013C$$

As might be expected dry matter increased with increasing water content and decreased with increasing penetrometer resistance of the soil. The percentage of variance accounted for water content C and penetrometer P resistance was 58.1 and 67.5 respectively.

It may be concluded that at low water content of the soil, the effect of aggregate size and crust strength on plant emergence is related to the water content of the crust. Emergence of wheat plants is seriously diminished or completely stopped when crust strength as measured with penetrometer resistance increased from 90 to 340 kPa. However the conclusions drawn here must be viewed in the light of the facts that specific environmental conditions maintained around the pots and that no water was added to the soil after the experiment was started. The ability of the plants to emerge may have been decreased by water stress.

SECTION 5. GENERAL DISCUSSION AND CONCLUSIONS

The objective of the study was to examine the effects of the size and stability of aggregates on growth of wheat with a view of defining optimum structural conditions in the seed-bed. In particular it set out

a) to obtain a quantitative description of the structure of the seed-bed and changes of the structure with time;

b) to examine the effects of the size and stability of aggregates in stratified seed-beds on water potential and temperature of the soil; and

c) to examine the effects of the conditions in the seed-bed on germination, emergence, establishment and yield of wheat.

In this study, sieved aggregates were used to make the seed-beds. Seed-beds prepared in this manner have a narrow size-range distribution and are not directly comparable to those formed by tillage implements which produce a wide range of aggregate sizes. The method also necessitates the use of small plots which tend to minimise the differences between treatments and increase variability in the later stages of growth as a result of the edge effect. Nevertheless, the use of sieved aggregates enables seed-beds with a well defined and reproducible structure to be made, and it provides a means by which seed-beds can be compared quantatively in space and in time.

The criteria used to evaluate the suitability of the various seed-beds for cereals were germination, date of emergence, total emergence and yield of wheat. In the early stages of plant growth, the date of emergence was the only factor affected by the aggregate size treatments. Plants emerged earlier in finer seed-beds (2 - 4/< 2 mm, and unsorted aggregates < 8 mm of which 60 % were < 2 mm). These results agree with those of Edwards (1957a), who found that barley and oats emerged earlier in finer seed-beds than in coarse ones. Taylor (1974) and Braunack (1979) obtained similar results for sorghum and wheat respectively. However there is a large variability in the size of aggregates found to be optimum for total plant emergence. With cereals for example Russell (1962), Greenland (1971) reported that aggregates 1 - 5 mm were desirable for a satisfactory plant emergence, while Edwards (1957a) found that smaller aggregates i.e. < 1 mm were more suitable for early growth of cereals. In other cases, larger aggregates allowed greater emergence. For example, Yoder (1937), Jain and Agrawal (1970) found that the emergence of cotton and sugar cane respectively was higher in seed-beds made of aggregates 4 - 8 mm diameter. The differences in results obtained by various authors may be due to differences in plant species and/or to differences in the soil and the conditions under which the different experiments were carried out. However most of the reports cited above are incomplete in that little information is provided on the conditions under which the experiments were carried out particularly with respect to water, temperature and aeration in the seed-beds and the extent to which these were determined by meteorological factors. In the present study it was found that between sowing and emergence, temperature at 4 cm depth (seed level) and 8 cm depth were not affected by aggregate size or aggregate stability, but soil water potential at 4 cm depth was higher (less negative) in seed-beds made of smaller aggregates (2 - 4/< 2 mm) than larger aggregates (4 - 8/2 - 4 mm and 4 - 8/< 2 mm). Temperature and water potential in seed-beds as influenced by meteorological factors can have a large effect on subsequent plant growth (Hay 1977; Hadas and Stibbe 1977; Braunack 1979). Although meteorological factors are most important, aggregate size and aggregate stability can have greater influence on soil environment than observed in the experiment described in Section 3 (Johnson and Henry 1964; Farrell *et al.* 1966; Gumbs and Warkentin 1975).

As noted by Braunack (1979), most workers apparently used stable aggregates and little mention was made of aggregate breakdown and the formation of soil crusts. The effects of variation in seasonal conditions on soil crusting and the consequences for plant emergence can be illustrated by the results obtained by Braunack (1979) and those obtained in the present experiment (Section 3). Both experiments used the same soil (Urrbrae loam), which is prone to crusting. Braunack (1979) found that the surface of seed-beds made of small aggregates (< 1 mm) readily formed a crust which significantly decreased the total emergence of wheat. However in the field experiment described in Section 3 crust formation and crust strength did not affect total emergence of the wheat. The difference in results obtained in these two cases may be attributed to the variation in seasonal conditions particularly rainfall which affected the strength of the crust. Rainfall was 206.9 mm of which 2 mm fell between sowing and emergence during the season Braunack (1979) conducted his experiment and 732 mm of which 30.6 mm fell between sowing and emergence during the season the present experiment (Section 3) was conducted. In the latter case the crust which formed remained soft and was easily penetrated by plants. Crust strength as measured by penetrometer resistance was 22 - 35 kPa compared with 40 - 50 kPa in Braunack's experiment. Crusts of strength between 50 and 140 kPa, as measured by modulus of rupture, have been found by other workers to decrease the emergence of wheat (Hanks and Thorp 1956, 1957). However the values obtained by these two methods of measuring crust strength are not equal. Braunack (1979) observed that, in general, crust strength as determined by modulus of rupture are smaller than that determined by hand penetrometer. Seedling emergence may not always be related to crust strength since so many other factors such as plant species, soil temperature and soil water can influence plant growth (Williams 1971; Jensen *et al.* 1972). Jensen *et al.* (1972) and Hadas and Stibbe (1977) found that water stress decreased the ability of seedlings to exert forces strong enough to break through the crust. It is likely that both water stress and crust strength influenced the emergence of wheat in the glasshouse experiment reported in Section 4.

While crust formation may not always be of great importance in determining total plant emergence, it is an undesirable feature of seed-beds, in that it can decrease water infiltration and it may lead to surface run-off and soil erosion (Oades 1976). It was shown in Section 4 that percolation of water through the soil was significantly decreased by the presence of the crust which formed at the surface of beds made of aggregates untreated with P.V.A. The presence of stable aggregates at the surface of the seed-beds permits satisfactory rates of water infiltration to be maintained because stable aggregates are more able to keep an open structure with adequate macroporosity (Mazurak and Mosher 1970; Ojeniyi 1978). In the field experiment (Section 3) the proportions of pores > 1, > 2, > 4 and > 8 mm intercepted length were significantly ($P = 0.05$) higher at all times of sampling where aggregates were stabilised by treatment with P.V.A. than where the soil was untreated. Treated aggregates 4 - 8 and 2 - 4 mm diameter could withstand rainfall for a longer time than untreated aggregates of the same size range. This can be of great importance as far as run-off and soil erosion are concerned. However, the distribution and intensity of rainfall (Fig. 5) during the season in which the experiment was carried out was such that the no run-off occurred, even where P.V.A. was not applied.

Other properties of seed-beds can influence plant growth. The availability of nutrients may be affected by the characteristics of different sized aggregates such as their organic matter and clay content (which, in the study present here was similar for all aggregates) or by differences in the environmental conditions which they produce in the seed-beds (Hagin 1952, 1956; Larson 1964; Tabatabai and Hanway 1968b;

Hillel and Hadas 1972). There was evidence that N availability to the plants in the field experiment (Section 3) was affected by both the size and stability of aggregates. The concentration and total content of N in the plants at tillering and harvest was higher in plants from plots made of aggregates 2 - 4/< 2 mm than in plants from plots made of aggregates 4 - 8/2 - 4 mm and 4 - 8/< 2 mm and the difference in N content was greater when aggregates were treated with P.V.A. than when untreated. Plants with higher nitrogen content produced the highest dry matter and grain yields. Oades (1976) observed that signs of N deficiency at the 3 to 5 week old wheat plants in the field were related to treatment of soil with P.V.A.. However dry matter and grain yield were not affected. The leaching and incubation experiments (Section 4) were undertaken to determine the likelihood of mineralisation and/or leaching of N being involved in the production of different yields by plants in different seed-beds. Although loss of N by denitrification cannot be completely discounted, denitrification was not investigated here because previous work on this soil by Stefanson and Greenland (1970) and Stefanson (1972a) had shown that gaseous losses were low from freely drained sites. Moreover, plants with the highest nitrogen contents in the present study were found under conditions not likely to favour denitrification. The results of the experiments suggest that mineralisation of N in the field was unlikely to have been much affected by aggregate size or aggregate stability, but increased leaching of N brought about by treatment of aggregates with P.V.A. and increased water percolation may have been largely responsible for lower uptake of N by plants in plots thus treated. The likelihood of N being leached completely from the soil within the root zone in semi-arid environments is not great. It depends on the seasonal conditions and in particular the intensity and quantity of rainfall. Some of the nitrogen leached may move back in the topsoil, following the upward water movement due to evaporation, and may be available for uptake by plants later in the season. This uptake will depend on the depth at which N is localised in the soil and on the depth and density of the plant roots (Boswell and Anderson 1970). The effect of plants on leaching of N was not investigated here. Generally, the presence of plants will decrease losses of N by leaching through absorption by actively growing roots and immobilisation by associated micro-organisms (Boswell and Anderson 1970). The presence of N fertilizer on net mineralisation of N in the soil in different treatments remains to be tested. Broadbent (1965) reported that the presence of N fertilizer had a stimulating effect on mineralisation of organic N in the soil. This stimulation was attributed to the increased biological activity in the soil when N fertilizer was added. However, in the field experiment, N fertilizer was added to all the plots and the conclusions drawn are likely to remain the same.

Stratification of seed-beds is a more realistic approach to study seed-beds as in practice, the sorting action of implements causes the formation of more or less stratified seed-beds with a greater proportion of the larger aggregates near the surface and a greater proportion of the smaller aggregates towards the bottom of the seed-bed. The large aggregates at the surface provide an effective method of increasing aeration as the results of soil structure measurements (Section 3) have shown. When aggregates are unstable, larger aggregates at the surface can withstand rainfall for a longer period and decrease the risk of soil crusting. The fine aggregates in the lower layer should provide a better seed-soil contact. However in the present study the increase of aggregate size from < 2 mm to 2 - 4 mm in the lower layer of seed-beds did not affect the properties of seed-beds (temperature, water potential) and the performance of plants. But in different seasonal conditions (drier conditions) different results may be obtained as far as germination and plant emergence are concerned. Further investigations on stratified seed-beds in different seasonal conditions are required as they have the potential for conserving water in the seed-bed by reducing evaporation (Johnson and Buchele 1961; Hillel and Hadas 1972; Hadas 1975; Braunack 1979). The performance of plants in stratified seed-beds in different seasonal conditions need also to be tested on the experimental level and in practice by attempting to obtain the desired distribution or aggregates by tillage.

In conclusion, it may be suggested that where the soil is stable, seed-beds made of aggregates 2 - 4 mm may be the most suitable for cereals in regions with environmental conditions similar to those under which the experiment was conducted, where seed-beds made of aggregates 2 - 4/< 2 mm had the highest water potential (less negative), had the earliest emergence and the highest dry matter production and grain yield. However when the aggregates are unstable and the soil is prone to crust formation, larger aggregates (4 - 8 mm) may be desirable at the surface of seed-beds for the reasons mentioned above.

Properties of seed-beds (temperature, water potential, aeration) and their effects on plant emergence and establishment vary with seasonal conditions and any suggestion on suitable seed-bed for an optimum plant performance should be seen in the light of environmental conditions.

Stable aggregates result in a higher water infiltration and a higher leaching of N and that leaching of N may be severe enough to affect plant yield.

Net mineralisation of N in Urrbrae soil unaffected by size of aggregates between < 2 and 4 - 8 mm diameter. Treatment of the soil with P.V.A. also had no effect on mineralisation of N.

BIBLIOGRAPHY

ABROL, I.P. and PALTA, J.P. (1970). A study of the effect of aggregate size and bulk density on moisture retention characteristics of selected soils.
Agrochimica 14 : 157-165.

ALDERFER, R.B. and MERKLE, F.G. (1941). The measurement of structural stability and permeability and the influence of soil treatments upon these properties.
Soil Sci. 51 : 201-211.

ALDERFER, R.B. and MERKLE, F.G. (1942). The comparative physical constitution of water-stables granules and of the original soil.
Soil Sci. 53 : 105-113.

ALDERMAN, J.K. (1956). The erodibility of granular materials.
J. Agric. Enging. Res. 1 : 136-142.

ALISON, F.E. (1966). The fate of nitrogen applied to soils.
Advance Agron. 18 : 219-258.

ALLMARAS, R.R., NELSON, W.W. and HALLAUER, E.A. (1972). Fall versus spring ploughing and related soil heat balance in the western corn belt.
Agric. Exp. Sta. Univ. Minn. Tech. Bull. 283.

AMEMIYA, M. (1965). The influence of aggregate size on soil moisture content-capillary conductivity relations.
Soil Sci. Soc. Amer. Proc. 29 : 744-748.

ARNDT, W. (1965a). The nature of mechanical impedance to seedlings by soil surface seals.
Aust. J. Soil Res. 3 : 45-54.

ARNDT, W. (1965b). The impedance of soil seals and the forces of emerging seedlings.
Aust. J. Soil Res. 3 : 55-68.

ASHRAF, C.M. and ABU-SHAKRA, S. (1978). Wheat germination under low temperature and moisture stress.
Agron. J. 70 : 135-139.

BARTHOLOMEW, W.V. and CLAR, F.E. (1965). Soil nitrogen.
American Society of Agronomy, Madison Inc. Wisconsin.

BATES, T.E. and TISDALE, S.L. (1957). The movement of nitrate nitrogen through soil columns of coarse textured soil materials.
Soil Sci. Soc. Amer. Proc. 21 : 525-528.

BATEY, T. and DAVIES, B.D. (1971). Soil structure and the production of arable crops.
J. Roy. Agric. Soc. Eng. 132 : 106-122.

BAVER, L.D. and RHOADES, H.F. (1932). Aggregate analysis as an aid in the study of soil structure relationships.
J. Amer. Soc. Agron. 24 : 920-930.

BAVER, L.D. (1956). Soil physics.
(3rd Ed.). John Wiley, New York.

BAVER, L.D., GARDNER, V.H. and GARDNER, W.R. (1972). Soils physics.
(4th Ed.). John Wiley, New York.

BELAN, J. and COPPENET, M. (1980). Essai d'etude de la dynamic de
l'azote A l'aide de la lysimetrie.
Acad. Agric. de France. Comptes rendus 66 (2) : 1079-1087.

BENNETT, O.L., ASHLEY, D.A. and DOSS, B.D. (1964). Methods of reducing
soil crusting to increase cotton seedling emergence.
Agron. J. 56 : 162-165.

BENOIT, G.R. (1973). Effect of freeze-thaw cycles on aggregate stability
and hydraulic conductivity of three soil aggregate sizes.
Soil Sci. Soc. Amer. Proc. 37 : 3-5.

BHUSHAN, L.S. and GHILDYAL, B.P. (1971). Influence of shape of implements
on soil structure.
Ind. J. Agric. Sci. 41 : 744-751.

BHUSHAN, L.S. and GHILDYAL, B.P. (1972). Influence of radius of curvature
of mouldboard on soil structure.
Ind. J. Agric. Sci. 42 : 1-5.

BHUSHAN, L.S., VARADE, S.B. and GUPTA, C.P. (1973). Influence of tillage
practices on clod size, porosity and water retention.
Ind. J. Agric. Sci. 43 : 466-471.

BHUSHAN, L.S., VARADE, S.B. and GUPTA, C.P. (1974).
J. Agric. Engng. 11 : 20-24.

BISAL, F. and NIELSEN, K.F. (1967). Effect of frost action on the size
of soil aggregates.
Soil Sci. 104 : 268-272.

BLAVIA, F.J., MOLDENHAUER, W.C. and LAW, D.E. (1971). Materials for
stabilizing surface clods of cropped soils.
Soil Sci. Soc. Amer. Proc. 35 : 119-122.

BOSWELL, F.C. and ANDERSON, O.F. (1964). Nitrogen movement in
undisturbed profiles of fallowed soils.
Agron. J. 56 : 278-281.

BOSWELL, F.C. and ANDERSON, O.E. (1970). Nitrogen movement comparisons
in cropped versus fallowed soils.
Agron. J. 62 : 499-503.

BOYOUCOUS, G.J. (1935). Method for making mechanical analysis of the
ultimate natural structure of soil.
Soil Sci. 40 : 481-485.

BRAUNACK, M.V. (1979). Properties of aggregated seed-beds.
Unpubl. Ph. D. Thesis, Univ. of Adelaide.

BREMNER, J.M. (1965). Total nitrogen. In methods of soil analysis.
Part 2 (C.A. Black, Ed.). pp. 1149-1178.
American Society of Agronomy, Madison, Wisconsin.

BROADBENT, F.E. (1965). Effect of fertilizer nitrogen on release of soil nitrogen.
Soil Sci. Soc. Amer. Proc. 29 : 692-696.

BURFORD, J.R. and GREENLAND, D.J. (1970). Denitrification under an annual pasture.
11th Int. Grassland Congress, Queensland. pp. 458-461.

BURFORD, J.R. and STEFANSON, R.C. (1973). Measurement of gaseous losses of nitrogen from soils.
Soil Biol. Biochem. 5 : 133-141.

CARR, C.E. and GREENLAND, D.J. (1975). Soil conditioners.
Reports on the progress of applied chemistry during 1974, 59 : 269-290.

CARY, J.W. and EVANS, D.D. (1974). Soil crusts.
Agric. Exp. Sta. Univ. Arizona Techn. Bull. 214.

CHEPIL, W.S. (1953). Field structure of cultivated soils with special reference to erodability by wind.
Soil Sci. Soc. Amer. Proc. 17 : 185-190.

CHEPIL, W.S. (1954). Seasonal fluctuations in soil structure and erodability of soil by wind.
Soil Sci. Soc. Amer. Proc. 18 ; 13-18.

CHEPIL, W.S. (1955). Effect of asphalt on some phases of soil structure and erodability by wind.
Soil Sci. Soc. Amer. Proc. 19 : 125-128.

CHEPIL, W.S. (1958). The use of evenly spaced hemispheres to evaluate aerodynamic forces on the soil surface.
Trans. Amer. Geophy. Union 39 : 397-404.

CHEPIL, W.S. and WOODRUFF, N.P. (1963). The physics of wind erosion.
Adv. Agron. 15 : 211-302.

CLEMENT, C.R. and WILLIAMS, T.E. (1958). An examination of the method of aggregate analysis by wet sieving in relation to the influence of diverse leys on arable soils.
J. Soil Sci. 9 : 252-266.

CLEMENT, C.R. (1961). Benefit of leys - structural improvement or nitrogen reserves.
J. Brit. Grassl. Soc. 16 : 194-200.

COLE, R.C. and EDLEFSEN, N.E. (1935). A sedimentation tube for analysing water-stable soil aggregates.
Soil Sci. 40 : 473-479.

COLLIS-GEORGE, N. and LAL, R. (1970). Infiltration into columns of swelling soil as studied by high speed photography.
Aust. J. Soil Res. 8 : 195-207.

COLLIS-GEORGE, N. and LARYEA, K.B. (1971). Infiltration behaviour of structurally unstable soils under pounded and non pounded conditions.
Aust. J. Soil Res. 9 : 7-20.

COLLIS-GEORGE, N. and LARYEA, K.B. (1972). An examination of the wet aggregate analysis, the moisture characteristic, and infiltration-percolation methods of determining the stability of soil aggregates.
Aust. J. Soil Res. 10 : 15-24.

COLLIS-GEORGE, N. and LLOYD, J.E. (1978). Description of seed-beds in terms of shear strength. In "modification of soil structure". (EMERSON, W.W., BOND, R.D. and DEXTER, A.R. eds.)
John Wiley, London.

CORNFORTH, J.S. (1968). The effect of the size of soil aggregates on nutrient supply.
J. Agric. Sci. 70 : 83-85.

CRASWELL, E.T., SAFFIGNA, P.G. and WARING, S.A. (1970). The mineralisation of organic nitrogen in dry soil aggregates of different sizes.
Plant Soil 33 : 279-289.

CRASWELL, E.T. and WARING, S.A. (1972). Effect of grinding or decomposition of soil organic matter. I. The mineralisation of organic nitrogen in relation to soil type.
Soil Biol. Biochem. 4 : 427-433.

CUNNINGHAM, R.K. and COOKE, G.W. (1958). Soil nitrogen. II Changes in levels of inorganic nitrogen in a clay loam soil caused by fertilizer additions, by leaching and uptake by grass.
J. Sci. Food Agric. 9 : 317-324.

CURRIE, J.A. (1961). Gaseous diffusion in the aeration of aggregated soils.
Soil Sci. 92 : 40-45.

CURRIE, J.A. (1965). Diffusion within soil macro-structure: a structural parameter for soils.
J. Soil Sci. 16 : 279-289.

DANIELSON, R.E. (1972). Optimizing the soil physical environment toward greater crop yields.
Academic Press Inc., New York.

DECKER, W.L. (1957). Determination of soil temperature from meteorological data.
Iowa St. Coll. J. Sci. 31 : 389-390.

DE VRIES, D.A. (1963). Thermal properties of soils. 'In physics of plant environment'. (W.R. Van Wijk ed.).
North Holland Publ. Co., Amsterdam, pp. 210-235.

DEXTER, A.R. (1976). Internal structure of tilled soil.
J. Soil Sci. 27 : 267-278.

DEXTER, A.R. and HEWITT, J.S. (1978). The structure of beds of spherical particles.
J. Soil Sci. 29 : 146-155.

DEXTER, A.R. (1978). A stochastic model for the growth of roots in tilled soil.
J. Soil Sci. 29 : 491-502.

DOYLE, J.J. and MacLEAN, A.A. (1958). The effect of soil aggregate size on availability of oxygen and on growth of tomatoes.
Can. J. Soil Sci. 38 : 143-146.

EDWARDS, R.S. (1957a). Studies of the growth of cereals on seed-beds prepared by dry-sieving of the soil.
Emp. J. Exp. Agric. 25 : 167-184.

EDWARDS, R.S. (1957b). Studies of the growth of cereals on seed-beds prepared by dry-sieving of the soil. II. Post emergence, survival and development.
Emp. J. Exp. Agric. 25 : 304-320.

EDWARDS, R.S. (1958). Studies of the growth of cereals on seed-beds, prepared by dry-sieving of the soil. III. The yields of grain and of straw.
Emp. J. Exp. Agric. 26 : 323-343.

EDWARDS, A.D. and BREMNER, J.M. (1967). Microaggregates in soils.
J. Soil Sci. 18 : 64-73.

ELLISON, W.D. and SLATER, C.S. (1945). Factors that affect surface sealing and infiltration of exposed soil surfaces.
Agric. Engng. 26 : 156-157, 162.

EMERSON, W.W. (1959). The structure of soil crumbs.
J. Soil Sci. 10 : 235-244.

FARRELL, D.A., GREACEN, E.L. and GURR, G.G. (1966). Vapour transfer in soil due to air turbulence.
Soil Sci. 102 : 303-315.

FEODOROF, A. and RAFI, M. (1963). Evaporation of water from bare soil. The effect of structure condition.
Ann. Agron. 14 : 601-613.

FITTS, J.W. (1953). A nitrification procedure for predicting the availability of nitrogen to corn of Iowa soils.
Iowa State Coll. J. Sci. 27 : 172-173.

GAREY, C.L. (1954). Properties of soil aggregates. I. Relation to size, water stability and mechanical composition.
Soil Sci. Soc. Amer. Proc. 18 : 16-18.

GASSER, J.K.R. (1959). Soil nitrogen. IV. Transformations and movement of fertilizer nitrogen in a light soil.
Soil Sci. Food Agric. 10 : 192-197.

GORING, C.A. and CLARK, F.E. (1948). Influence of crop growth on mineralisation of nitrogen in the soil.
Soil Sci. Soc. Amer. Proc. 13 : 261-216.

GRABLE, A.R. and SIEMER, E.G. (1968). Effects of bulk density, aggregate size and soil water suction on oxygen diffusion, redox potentials and elongation of corn roots.
Soil Sci. Soc. Amer. Proc. 32 : 180-186.

GRADWELL, M.W. (1973). Internal properties of soil aggregates from the market gardens of Pukekohe.
N.Z. J. Agric. Res. 16 : 463-475.

GREACEN, E.L. (1958). The soil structure profile under pastures.
Aust. J. Agric. Res. 9 : 129-137.

GREENLAND, D.J. (1971). Changes in the nitrogen status and physical conditions of soils under pastures with special reference to the maintenance of fertility of Australian soils used for growing wheat.
Soils and Fertilizers 34 : 237-251.

GREENWOOD, D.J. and GOODMAN, D. (1967). Direct measurement of the distribution of oxygen in soil aggregates and in columns of fine soil crumbs.
J. Soil Sci. 18 : 182-196.

GUMBS, F.A. and WARKENTIN, B.P. (1975). Prediction of infiltration of water into aggregated clay soil samples.
Soil Sci. Soc. Amer. Proc. 39 : 255-263.

GUMBS, F.A. and WARKENTIN, B.P. (1976). Bulk density, saturation water content and rate of wetting of soil aggregates.
Soil Sci. Soc. Amer. Proc. 40 : 28-33.

HADAS, A. (1975). Drying of layered soil columns under non isothermal conditions.
Soil Sci. 119 : 143-148.

HADAS, A. (1977). Heat transfer in dry aggregated soil. I. Heat conductions.
Soil Sci. Soc. Amer. Proc. 41 : 1055-1059.

HADAS, A. and STIBBE, E. (1977). Soil crusting and emergence of wheat seedlings.

HAGIN, J. (1952). Influence of soil aggregation on plant growth.
Soil Sci. 74 : 471-478.

HAGIN, J. (1956). Utilisation of fertilizer nitrogen by plants in soils of different structure.
Plant Soil 8 : 33-41.

HAGIN, J. and HALEVY, J. (1961). Comparison of nitrification methods for estimating available nitrogen and validation of methods for evaluating the nitrogen requirements of hybrid corn.
Israel J. Agric. Res. 11 (2) : 81-88.

HAMMERTON, J.L. (1961a). Studies of the effects of soil aggregate-size on the emergence and growth of beet (*Beta Vulgaris* L.).
I. Seedling emergence.
J. Agric. Sci. 56 : 213-228.

HAMMERTON, J.L. (1961b). Studies of the effects of soil aggregate-size on the emergence and growth of beet (*Beta Vulgaris* L.)
J. Agric. Sci. 56 : 417-429.

HAMMERTON, J.L. (1963a). Studies of the effects of soil aggregate-size on the emergence and growth of beet (*Beta vulgaris* L.). III. Seedling growth.
Emp. J. Exp. Agric. 31 : 83-96.

HAMMERTON, J.L. (1963b). Studies of the effects of aggregate-size on the emergence and growth of beet (*Beta vulgaris* L.).
Emp. J. Exp. Agric. 31 : 83-96.

HANKS, R.J. and THORP, F.C. (1956). Seedling emergence of wheat, grain sorghum and soybeans as influenced by soil crust strength and moisture content.
Soil Sci. Soc. Amer. Proc. 21 : 357-359.

HANKS, R.J. and THORP, F.C. (1957). Seedling emergence of wheat, grain sorghum and soybeans as influenced by soil crust strength and moisture content.
Soil Sci. Soc. Amer. Proc. 21 : 357-359.

HANKS, R.J. and WOODRUFF, N.P. (1958). Influence of wind on water vapour transfer through soil, gravel and straw mulches.
Soil Sci. 86 : 160-165.

HANKS, R.J. (1960). Soil crusting and seedling emergence.
Trans. 7th Inter. Cong. Soil Sci. 1 : 340-346.

HARMSEN, G.W. and KOLENBRANDER, G.J. (1965). Soil inorganic nitrogen.
In: Bartholomew, W.V. and Clark, F.C. (Eds.)
American Soc. of Agron. Inc. Madison Wisconsin

HARMSEN, G. W. and van SCHREVEN, D. A. (1955). Mineralization of organic nitrogen in soil.
Adv. Agron. 7: 299-398.

HAY, R.K.M. (1977). Effects of tillage and direct drilling on soil temperature in winter.
J. Soil Sci. 28 : 403-409.

HEWITT, J.S. and DEXTER, A.R. (1979). An improved model of root growth in structured soil.
Plant Soil 52 : 325-343.

HIDE, J.C. and METZGER, W.H. (1939). Soil aggregation as affected by certain crops and organic materials and some chemical properties associated with aggregation.
Soil Sci. Soc. Amer. Proc. 4 : 19-22.

HILLEL, D. (1972). Optimizing of soil physical environment toward greater crop yields.
Academic Press Inc., New York.

HILLEL, D. and HADAS, A. (1972). Isothermal drying of structurally layered soil columns.
Soil Sci. 113 : 30-35.

HOLMES, J.W., GREACEN, E.L. and GURR, C.G. (1960). The evaporation of water from base soils with different tilths.
Trans. 7th Inter. Cong. Soil Sci. 1 : 188-194.

HOYLE, B.J., YAMADA, H. and HOYLE, T.D. (1972). Aggresizing to eliminate objectionable soil clods.
Calif. Agric. 26 : 3-5.

HOYLE, B.J. and YAMADA, H. 1975). Seed-beds and aggregate stability improved by rototilling wet soil. In 'soil conditioners'.
Special Publ. Soil Sci. Soc. Amer. No. 7, pp. 111-128.

JAGGI, I.K., GORANTIWAR, S.M. and KHANNA, S.S. (1972). Effect of bulk density and aggregate size on wheat growth.
Indian Soc. Soil Sci. 20 (4) : 421-423.

JAIN, N.K. and AGRAWAL, J.P. (1970). Effect of clod size in the seed-bed on development and yield of sugar cane.
Soil Sci. Soc. Amer. Proc. 34 : 795-797.

JENSEN, E.H., FRELICH, J.R. and GIFFOR, R.O. (1972). Emergence force of forage seedlings.
Agron. J. 64 : 635-639.

JOHNSON, W.H. and TAYLOR, G.S. (1960). Tillage treatments for corn on clay soils.
Trans. ASAE 3 : 4-7, 70.

JOHNSON, W.H. and BUCHELE, W.R. (1961). Influence of soil granule size and compaction on rate of soil drying and emergence of corn.
Trans. ASAE 4 : 170-174.

JOHNSON, W.H. and HENRY, J.E. (1964). Influence of simulated row compaction on seedling emergence and soil drying rates.
Trans. ASAE 7 : 252-255.

JUO, A.S.R. and LAL, R. (1975). Effect of continuous cropping and residue management on the chemical and physical properties of an alfisol in southern Nigeria.
Agron. Abstr. A.S.A. 38.

KEAY, J. and MENAGE, P.M.A. (1970). Automated determination of ammonium and nitrate in soils extracts by distillation.
Analyst (London) 95 : 379-382.

KIMBALL, B.A. and LEMON, E.R. (1971). Air turbulence effect upon soil gas exchange.
Soil Sci. Soc. Amer. Proc. 35 : 16-21.

KOHNKE, H. (1968). Soil physics.
McGraw-Hill Book Co., New York

KOHLENBRANDER, G. R. (1970). Calculation of parameters for the evaluation of the leaching of salts under field conditions.
Plant Soil 32: 439-453.

KOUWENHOVEN, J.K. and TERPSTRA, R. (1977). Sorting of glass spheres by tines.
J. Agric. Engng. Res. 22 : 153-163.

LARSON, W.E. (1964). Soil parameters for evaluating tillage methods and operations.
Soil Sci. Soc. Amer. Proc. 28 : 118-122.

LEMON, E.R. (1956). The potentialities for decreasing soil moisture evaporation loss.
Soil Sci. Soc. Amer. Proc. 20 : 120-125.

LEMOS, P. and LUTZ, J.F. (1957). Soil crusting and some factors affecting it.
Soil Sci. Soc. Amer. Proc. 21 : 485-491.

LONG, F.L. and HUCK, M.G. (1980). Nitrate movement under corn and fallow conditions.
Soil Sci. Soc. Amer. Proc. 44 : 787-793.

LOW, A.J. (1954). The study of soil structure in the field and in the laboratory.
J. Soil Sci. 5 : 57-74.

LOW, A.J. (1955). Improvement in the structural state of soils under leys.
J. Soil Sci. 6 : 179-199.

LYLES, L. and WOODRUFF, N.P. (1962). How moisture and tillage affect soil cloddiners for wind erosion control.
Agric. Engng. 43 : 150-153.

MARSHALL, T.J. (1962). The nature, development and significance of soil structure.
Trans. Joint Meeting Comm. IV and V Int. Soc. Soil Sci. N.Z. pp. 234-257.

MARTEL, Y.A. and PAUL, E.A. (1974). Effects of cultivation on the organic matter of grassland soils as determined by fractionation and radiocarbon dating.
Can. J. Soil Sci. 54 : 419-426.

MAZURAK, A.P. and MOSHER, P.N. (1970). Detachment of soil aggregates by simulated rainfall.
Soil Sci. Soc. Amer. Proc. 34 : 798-800.

MAZURAK, A. P., VALASSIS, V. T. and HARRIS, L. C. (1954). Water stability of aggregates from potato plots as affected by different rotation systems under irrigation in western Nebraska.
Soil Sci. Soc. Amer. Proc. 18: 243-247.

McINTYRE, D.S. (1955). Effect of soil structure on wheat germination in a red-brown earth.
Aust. J. Agric.Res. 6 : 797-803.

MILLER, S.A. and MAZURAK, A.P. (1958). Relationships of particle and pore sizes to the growth of sunflowers (*Helianthus annuas* L.)
Soil Sci. Soc. Amer. Proc. 22 : 275-278.

MOLDENHAUER, W.C. and LONG, D.C. (1964). Influence of rainfall energy on soil loss and infiltration rates. I. Effect over a range of texture.
Soil Sci. Soc. Amer. Proc. 28 : 813-817.

MOLDENHAUER, W.C., WISCHMEIER, W.H. and PARKER, D.D. (1967). The influence of crop management on run-off, erosion and soil properties of a Marshall silty clay loam.
Soil Sci. Soc. Amer. Proc. 31 : 541-546.

MOLDENHAUER, W.C. and KOSWARA, J. (1968). Effect of initial clod size on characteristics of splash and wash erosion. Soil Sci. Soc. Amer. Proc. 32 : 875-879.

MOLDENHAUER, W.C. and KEMPER, W.D. (1969). Interdependance of water drop energy and clod size on infiltration and clod stability. Soil Sci. Soc. Amer. Proc. 33 : 297-301.

MOLDENHAUER, W.C. (1970). Influence of rainfall energy on soil loss and infiltration rates. II. Effect of clod size distribution. Soil Sci. Soc. Amer. Proc. 34 : 673-677.

MYERS, R.J.K. and PAUL, E.A. (1971). Plant uptake and immobilisation of ^{15}N-labelled ammonium nitrate in field experiment with wheat. In: Nitrogen-15 in soil plant studies. IAIA Vienna Austria.

NEWMAN, E.I. (1966). A method of estimating the total length of root in a sample. J. Appl. Ecol. 3 : 139-145.

NIELSEN, D.R. (1976). Solute and water movement under arid and semi-arid regions. IAEA Technical Document No. 192 Vienna Austria.

NIJHAWAN, S.D. and DHINGRA, L.R. (1947). Some characteristics of soil aggregates in cultivated soils of Punjab, India. Soil Sci. Soc. Amer. Proc. 12 : 39-43.

OADES, J.M. (1976). Prevention of crust formation in soils by poly (vinyl alcohol). Aust. J. Soil Res. 14 : 139-148.

OJENIYI, S.O. (1978). Tilth structure and soil physical conditions. Unpubl. Ph. D. thesis, Univ. of Adelaide.

PAGE, E.R. (1979). The effect of poly (vinyl alcohol) on the crust strength of silty soils. J. Soil Sci. 30: 643-651.

PAWLOSKI, M.C. and SHAYKEWICH, C.F. (1972). Germination of wheat affected by soil water stress. Can. J. Plant Sci. 52 : 619-623.

PERCIVAL, J. (1921). The wheat plant. A monograph. Duckworth and Co., London.

PHILLIPS, R.E. and KIRKHAM, D. (1962). Soil compaction in the field on corn growth. Agron. J. 54 : 29-33.

PIPER, C.S. (1938). The red-brown earth of South Australia. Roy. Soc. Sth. Aust. Trans. 62 : 53-100.

PIZER, N.H. (1961). Soil structure in farming. J. Roy. Agric. Soc. Eng. 122 : 7-25.

RAI, K.D., RANEY, W.A. and VANDERFORD, H.B. (1954). Some physical factors that influence erosion and the influence of aggregate size and stability on growth of tomatoes. Soil Sci. Soc. Am. Proc. 18 : 486-489.

READ, D.W.L. and BEATON, J.D. (1963). Effect of fertilizer, temperature and moisture on germination of wheat. Agron. J. 55 : 287-290.

RIDLEY, A.O. and HEDLIN, A.O. (1968). Soil organic matter and crop yields as influenced by frequency of summer fallowing. Can. J. Soil Sci. 48 : 315-322.

ROHWER, C. (1931). Evaporation from free water surfaces. U.S.D.A. Techn. Bull. No. 271.

ROSE, C.W. (1961). Rainfall and soil structure. Soil Sci. 91 : 49-54.

ROSE, C.W. (1968). Evaporation from bare soil under high radiation conditions. Trans. 9th Inter. Congr. Soil Sci. 1 : 57-66.

RUSSEL, W.E. (1961). Soil conditions and plant growth (9th ed.). Longmans, London.

SHANMUGATHAN, R.T. and OADES, J.M. (1982). Modification of soil physical properties. J. Soil Sci. 33, 451-465.

SIDDOWAY, F.H. (1963). Effects of cropping and tillage methods on dry aggregate soil structure. Soil Sci. Soc. Amer. Proc. 27 : 452-454.

SEIFERT, J. (1964). Influence of size of soil structural aggregates on the degree of nitrification. Folia. Microbial. Praha. 9 : 115-120.

SILLANPAA, M. and WEBBER, L.R. (1961). The effect of freezing-thawing and wetting-drying cycles on soil aggregation. Can. J. Soil Sci. 41 : 182-187.

SINGH, N.T. and DHALIWAL, G.S. (1972). Effect of soil temperature on seedling emergence in different crops. Plant Soil 37 : 441-444.

SLATER, C.S. and RODRIGUES, A. (1954). Aspects of structure that affect germination in a silt loam soil. Soil Sci. Soc. Amer. Proc. 18 : 219-221.

STACE, H.C.T., HUBBLE, G.D., BREWER, R., NORTHCOTE, K.H., SLEEMAN, J.R., MULCAHY, M.J. and HALLSWORTH, E.G. (1968). A handbook of Australian soils. Rellim Glenside, Sth. Aust.

STEFANSON, R.C. and GREENLAND, D.J. (1970). Measurement of nitrogen and nitrous oxide evolution from soil-plant system using sealed growth chambers. Soil Sci. 109 : 203-206.

STEFANSON, R.C. (1972a). Soil denitrification in sealed soil-plant systems. II. Effect of soil water content and form of applied nitrogen.
Plant Soil 37 : 129-140.

STEFANSON, R.C. (1972b). Effect of plant growth and form of nitrogen fertilizer on denitrification from South Australian soils.
Aust. J. Soil Res. 10 : 183-195.

STEFANSON, R.C. (1973a). Relative rates of denitrification and non-symbiotic nitrogen fixation in the soil-plant system.
Soil Biol. Biochem. 5 : 869-880.

STEFANSON, R.C. (1973b). Polyvinyl alcohol as a stabilizer of surface soil.
Soil Sci. 115 : 120-128.

TABATABAI, M.A. and HANWAY, J.J. (1968a). Uptake of native potassium by plants from natural soil aggregates of different sizes.
Soil Sci. Soc. Amer. Proc. 32 : 546-549.

TABATABAI, M.A. and HANWAY, J.J. (1968b). Some chemical and physical properties of different sized natural aggregates from Iowa soils.
Soil Sci. Soc. Amer. Proc. 32 : 588-591.

TAMBOLI, P.M. (1961). The influence of bulk density and aggregate size on soil moisture retention.
Ph. D. Thesis, Iowa State Univ. Cited by LARSON, W.E. (1964).

TAMBOLI, P.M., LARSON, W.E. and AMEMIYA, M. (1964). The influence of aggregate size on soil moisture retention.
Proc. Iowa Acad. Sci. 71 : 103-108.

TAYLOR, H.M. and RATLIFF, L.F. (1969). Root elongation rates of cotton and peanuts as a function of soil strength and soil water content.
Soil Sci. 96 : 153-156.

TAYLOR, M.S. (1974). The effect of soil aggregate size on seedling emergence and early growth.
East Afri. Agric. Forr. J. 40 : 204-213.

TEPE, W. and LEIDENFROST, E. (1958). Die kinehk der Bodenionem, gemessen mit coneaushauschen.
Forsch. 11 : 217-230 (Cited by Wiersum, L.D. (1962)).

TERRY, D.L. and McCANTS, C.B. (1968). The leaching of ions in soils.
North Carolina Agric. Exp. Sta. Techn. Bull. 184.

TERRY, D.L. and McCANTS, C.B. (1970). Quantitative prediction of leaching in field soils.
Soil Sci. Soc. Amer. Proc. 34 : 271-276.

THOMAS, G.W. (1970). Soil and climatic factors which affect nutrient mobility.
SSSA Special publication No. 4, Madison, Wisconsin.

THOW, R.F. (1963). The effect of tilth on the emergence of spring oats.
J. Agric. Sci. 72 : 33-46.

TISDALL, J.M.,COCKROFT, B. and UREN, N.C. (1978). The stability of soil aggregates as affected by organic materials, microbial activity and physical disruption.
Aust. J. Soil Res. 16 : 9-17.

TURCHENECK, L.W. and OADES, J.M. (1978). Organo-mineral particles in soils. In 'Modification of soil structure' (Ed. W.W. Emerson, R.D. Bond and A.R. Dexter). Wiley, London. pp. 137-44.

VLEK, P.L.G., FILLERY, I.R.P. and BURFORD, J.R. (1981). Accession, transformation and loss of nitrogen in soils of the arid region.
Plant Soil 58 : 133-175.

VOORHEES, W.B., ALLMARAS, R.R. and LARSON, W.E. (1966). Porosity of surface soil aggregates at various moisture potentials.
Soil Sci. Soc. Amer. Proc. 30 : 163-167.

VORONIN, A.D., MANUCHAROV, A.S. and POCHATKOVA, T.N. (1976). Density and porosity of soil aggregates of the dark chesnut and chesnut soil subzones.
Soviet Soil Sci. 8 : 77-84.

WALLACE, A. (1954). Ammonium and nitrate nitrogen absorption by citrus.
Soil Sci. 78 : 89-94.

WARING, S.A. and BREMNER, J.M. (1964). Effect of soil mesh size on the estimation of mineralizable nitrogen in soils.
Nature 202 : 1141.

WEAST, R.C. (1973). Handbook of chemistry and physics.
54th ed. CRS Press, Ohio.

WETSELAAR, R. (1961). Nitrate distribution in tropical soils. I. Possible causes of nitrate accumulation near the soil surface after a long dry period.
Plant soil. 15 : 110-120.

WETSELAAR, R. (1962). Nitrate distribution in tropical soils. III. Downward movement and accumulation of nitrate in the subsoil.
Plant soil. 16 : 19-31.

WILLIAMS, J. and SHAYKEWICH, C.F. (1971). Influence of water matric potential and hydraulic conductivity on the germination of rape (*Brassica napus* L.).

WILLIAMS, W. A. (1963). The emergence force of forage legume seedlings and their response to temperature.
Crop. Sci. 3: 472-474.

WIERSUM, L.K. (1962). Uptake of nitrogen and phosphorus in relation to soil structure and nutrient mobility.
Plant Soil 16 : 62-70.

WITTMUSS, H.D. and MAZURAK, A.P. (1958). Physical and chemical properties of soil aggregates in a Brunizem soil.
Soil Sci. Soc. Amer. Proc. 22 : 1-5.

WORT, D.J. (1940). Soil temperature and growth of Maquis wheat. Plant physiol. 15 : 335-342.

YODER, R.E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Amer. Soc. Agron. 28 : 337-351.

YODER, R.E. (1937). The significance of soil structure in relation to the tilth problem. Soil Sci. Soc. Amer. Proc. 2: 21-33.