Aggregate coalescence and factors affecting it

Thesis submitted by

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Summary

The phenomenon called *soil aggregate coalescence* occurs at contact-points between aggregates and causes soil strength to increase to values that can inhibit plant root exploration and thus potential yield. During natural wetting and drying, soil aggregates appear to 'weld' together with little or no increase in dry bulk density. The precise reasons for this phenomenon are not understood, but it has been found to occur even in soils comprised entirely of water stable aggregates. Soil aggregate coalescence has not been widely observed and reported in soil science and yet may pose a significant risk for crops preventing them from achieving their genetic and environmental yield potentials. This project used soil penetrometer resistance and an indirect tensile-strength test to measure the early stages of aggregate coalescence and to evaluate their effects on the early growth of tomato plants. The early stages of aggregate coalescence were thought to be affected by a number of factors including: the matric suction of water during application and subsequent drainage, the overburden pressure on moist soil in the root zone, the initial size of soil aggregates prior to wetting, and the degree of sodicity of the soil aggregates. Seven main experiments were conducted to evaluate these factors.

The matric suction during wetting of a seedbed affects the degree of aggregate slaking that occurs, and the strength of the wetted aggregates. The matric suction during draining affects the magnitude of 'effective stresses' that operate to retain soil structural integrity as the soil drains and dries out. An experiment was conducted to evaluate the influence of matric suction (within a range of suctions experienced in the field) on aggregate coalescence using soils of two different textures. Sieved aggregates (0.5 to 2 mm diameter) from a coarse-textured and two fine-textured (swelling) soils were packed into cylindrical rings (4.77 cm i.d., 5 cm high) and subjected to different suctions on wetting (near-saturation, and 1 kPa), and on draining (10 kPa on sintered-glass funnels, and 100 kPa on ceramic pressure plates). After one-week of drainage, penetrometer resistance was measured as a function of depth to approximately 45 mm (penetrometer had a recessed-shaft, cone diameter = 2 mm, advanced at a rate of 0.3 mm/min). Tensile strength of other core-samples was measured after air-drying using an indirect "Brazilian" crushing test. For the coarse-textured soil, penetrometer resistance was significantly greater for samples wet to near-saturation, despite there being no significant increase in dry bulk density; this was not the case for the finer-textured soils, and it was difficult to distinguish the effects of

variable bulk density upon drying from those of the imposed wetting treatments. In both coarse- and fine-textured soils, the tensile strength was significantly greater for samples wet to near-saturation. Thus wetting- and draining-suctions were both found to influence the degree of soil aggregate coalescence as measured by penetrometer resistance and tensile strength.

Aggregate coalescence in irrigated crops is known to develop as the growing season progresses. It was therefore thought to be linked to the repeated occurrence of matric suctions that enhance the phenomenon during cycles of wetting and draining. An experiment was conducted to determine the extent of aggregate coalescence in a coarse-textured and two fine-textured (swelling clay) soils during 8 successive cycles of wetting and draining. Sieved aggregates (0.5 to 2 mm diameter) from each soil were packed into cylindrical rings (4.77 cm i.d., 5 cm high) and wetted to near saturation for 24 h. They were then drained on ceramic pressure plates to a suction of 100 kPa for one week, after which penetrometer resistance and tensile strength were measured as described above. The degree of expression of aggregate coalescence depended on soil type. For the coarse-textured soil, repeated wetting and draining significantly increased bulk density, penetrometer resistance and tensile strength. For the fine-textured soil, penetrometer resistance and bulk density did not vary significantly with repeated wetting and draining; on the contrary, there was evidence in these swelling clay soils to suggest bulk density and penetrometer resistance decreased. However, there was a progressive increase in tensile strength as cycles of wetting and draining progressed. The expansive nature of the fine-textured soil appears to have masked the development of aggregate coalescence as measured by penetrometer resistance, but its expression was very clear in measurements of tensile strength despite the reduction in bulk density with successive wetting and draining.

Field observations have indicated that aggregate coalescence is first expressed at the bottom of the seedbed and that it develops progressively upward to the soil surface during the growing season. This suggests that overburden pressures may enhance the onset of the phenomenon by increasing the degree of inter-aggregate contact. Soils containing large quantities of particulate organic matter were known to resist the onset of aggregate coalescence to some extent. An experiment was conducted to evaluate the effects of soil organic matter and overburden pressures, by placing brass cylinders of various weights (equivalent to static load pressures of 0, 0.49, 1.47 and 2.47 kPa) on the top of dry soil aggregates (0.5 – 2 mm diameter) having widely different soil organic carbon contents placed in steel rings 5 cm high and 5 cm i.d. With the weights in place, the aggregates were wetted to near-saturation for 24 h and then drained on ceramic pressure plates to a suction of 100 kPa for one week. Bulk density, penetrometer resistance and tensile strength were measured when the samples were removed from the pressure plates and they all increased significantly with increasing overburden pressure in the soil with low organic matter content, but not in the soil with high organic matter content.

The amount of tillage used to prepare seedbeds influences the size distribution of soil aggregates produced – that is, more tillage produces finer seedbeds. The size distribution of soil aggregates affects the number of inter-aggregate contact points and this was thought to influence the degree of aggregate coalescence that develops in a seedbed. Previous work has shown that soil organic matter reduces aggregate coalescence and so an experiment was conducted to evaluate the effects of aggregate size and organic matter on the phenomenon. For soils with high and low organic matter contents, aggregate size fractions of < 0.5, 0.5 – 2, 2 – 4, and < 4 mm were packed into soil cores (as above) and wetted to near-saturation then drained to 100 kPa suction as described above. Penetrometer resistance and tensile strength were measured and found to increase directly with the amount of fine material present in the soil cores – being greater in the < 0.5 mm and < 4 mm fractions, and being less in the 0.5 – 2 mm and 2 – 4 mm fractions. In all cases, penetrometer resistance and tensile strength were lower in the samples containing more organic matter.

The rate at which soil aggregates are wetted in a seedbed affects the degree of slaking and densification that occurs, and the extent to which aggregates are wetted influences the overall strength of a seedbed. Both wetting rate and the extent of wetting were believed to influence the onset of aggregate coalescence and were thought to be affected by soil organic matter and irrigation technique. An experiment was therefore designed to separate these effects so that improvements to management could be evaluated for their greatest efficacy – that is, to determine whether management should focus on improving irrigation technique or increasing soil organic matter content, or both. The rate of wetting was controlled by spraying (or not spraying) soil aggregates (0.5 – 2 mm diameter) with polyvinyl alcohol (PVA). Samples of coarse- and fine-textured soils were packed into steel rings (as above) and subjected to different application rates of water (1, 10 and 100 mm/h) using a dripper system controlled by a peristaltic pump. Samples were brought to either a near-saturated state or to a suction of 10 kPa for 24 h, and then drained on a pressure plate at a suction of 100 kPa for one week. Measurements of penetrometer resistance and tensile strength were then made as described above. As expected, penetrometer resistance was lower in samples treated with PVA before wetting (slower wetting rates) and in samples held at a greater suction (10 kPa) after initial wetting (greater inter-aggregate strength). The effects were more pronounced in the coarse-textured soil. In both coarse- and fine-textured soils, tensile strengths increased with increasing wetting rate (greatest for 100 mm/h) and extent of wetting (greater when held at near-saturated conditions). The rate of wetting was found to be somewhat more important for promoting aggregate coalescence than the extent of wetting.

Because aggregate coalescence often occurs with little or no increase in bulk density, an explanation for the increase in penetrometer resistance and tensile strength is unlikely to be explained by a large increase in the number of inter-aggregate contacts. An increase in the strength of existing points of inter-aggregate contact was therefore considered in this work. For inter-aggregate bond strengths to increase, it was hypothesized that small increases in the amount of mechanically (or spontaneously) dispersed clay particles, and subsequent deposition at inter-aggregate contact points could increase aggregate coalescence as measured by penetrometer resistance and tensile strength. An experiment was devised to manipulate the amount of spontaneously dispersed clay in coarse- and fine-textured soils of high and low organic matter content. The degree of sodicity of each soil was manipulated by varying the exchangeable sodium percentage (ESP) of soil aggregates (0.5 – 2mm) above and below a nominal threshold value of 6. Dry aggregates were then packed into steel rings (as above) and subjected to wetting near saturation, then draining to a suction of 100 kPa for one week as described above. Measurements were then taken of penetrometer resistance and tensile strength, both of which were affected by ESP in different ways. In the coarse-textured soil, sodicity enhanced aggregate slaking and dispersion, which increased bulk density. While penetrometer resistance also increased, its effect on aggregate coalescence could not be separated from a simple effect of increased bulk density. Similarly, the effect of sodicity on aggregate coalescence in the fine-textured soil was confounded by the higher water contents produced by greater swelling, which produced lower-than-expected penetrometer resistance. Measurements of tensile strength were conducted on air-dry samples, and so the confounding effects of bulk density and water content were eliminated and it was found that tensile strength increased with sodicity in both coarse- and fine-textured soils. The presence of dispersed clay was therefore implicated in the development of aggregate coalescence in this work.

Finally, a preliminary evaluation of how the early stages of aggregate coalescence might affect plant growth was attempted using tomatoes (*Gross lisse*) as a test plant. Seeds were planted in aggregates (0.5 – 4 mm) of a coarse- or fine-textured soil packed in steel rings. These were wetted at a rate of 1 mm/h to either near-saturation (for maximum coalescence) or to a suction of 10 kPa (for minimum coalescence) and held under these conditions for 24 h. All samples were then transferred to a ceramic pressure plate for drainage to 100 kPa suction for one week. Samples were then placed in a growth-cabinet held at 20C with controlled exposure to 14 h light/day. Germination of the seeds, plant height, and number and length of roots were observed. Germination of the seeds held at near-saturation in both coarse- and fine-textured soils was delayed by 24 h compared with seeds held at 10 kPa suction. Neither the number nor the length of tomato roots differed significantly between the different treatments and soils. In the coarse-textured soil, however, the total root length over a period of 14 days was somewhat greater in the un-coalesced samples than in the coalesced samples, but this difference was not statistically significant. These results suggest that aside from delaying germination, aggregate coalescence may not have a large effect on early growth of tomato plants. However, this is not to say that detrimental effects may not be manifest at later stages of plant growth, and this certainly needs to be evaluated, particularly because aggregate coalescence increase with repeated cycles of wetting and draining.

In conclusion, the primary findings of the work undertaken in this thesis were:

- Rapid wetting of soil aggregates to near-saturation enhanced the onset of soil aggregate coalescence as measured by (in some cases) penetrometer resistance at a soil water suction of 100 kPa, and (in most cases) tensile strength of soil cores in the air-dry state. The rate of wetting appeared to be more important in bringing on aggregate coalescence than how wet the soil eventually became during wetting. This means reducing the rate at which irrigation water is applied to soils may reduce the onset of aggregate coalescence more effectively than controlling the total amount of water applied – though both are important.

- The literature reports that aggregate coalescence occurs in the field over periods of up to several months, involving multiple wetting and draining cycles, but the work here demonstrated that this can occur over much shorter time periods depending on conditions imposed.
- Aggregate coalescence occurred in coarse-textured soils regardless of whether the bulk density increased during wetting and draining. In finer-textured soils, the response to wetting conditions varied and was complicated by changes in bulk density and water content due to swelling.
- Small overburden pressures enhanced the onset of aggregate coalescence, but these effects were diminished in the presence of high soil organic matter contents.
- Finer aggregate size distributions (which are often produced in the field by excessive tillage during seedbed preparation) invariably led to greater aggregate coalescence than coarser aggregate size distributions. The effects of aggregate size were mitigated to some extent by higher contents of soil organic matter.
- Sodicity enhanced aggregate coalescence as measured by tensile strength, but when penetrometer resistance was measured in the moist state, the effects were masked to some extent by higher water contents generated by swelling and dispersion. This work suggests that tensile strength (in the air dry state) may be a more effective measure of aggregate coalescence than penetrometer resistance.
- Early plant response to aggregate coalescence was not large, but the response may become magnified during later stages of growth.

Statement

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Signed: Date: 12/09/2006

Uswah Hasanah

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Chapter 1 : Introduction, Literature Review and Aims

1.1. Introduction

Soil structural degradation that produces conditions less favourable for crop production has become a global phenomenon in agricultural soils. The extent of the degradation varies from soil to soil depending upon what causes it. The causes can be classified into four categories including mechanical compaction as a result of the use of heavy machinery (Hakansson and Voorhees, 1997; Brussard and van Faassen, 1994; Hakansson *et al.*, 1988; Jakobsen and Greacen, 1985), surface crusting due to raindrop impact (Sumner and Stewart, 1992; Bresson and Cadot, 1992; Le Bissonnais *et al.*, 1989; Levy *et al.*, 1986; Kemper and Miller, 1974), hardsetting because of soil structure collapse due to water unstable aggregates (Mullins *et al.*, 1990; Gusli *et al.*, 1994a,b), and aggregate coalescence of relatively water stable aggregates (Cockroft & Olsson, 2000, Ghezzehei and Or, 2000). Unlike the first three categories which have been extensively studied, there has been little published about coalescence. It is a soil condition in which aggregates become "welded" at their contact points (Bresson and Moran, 1995; Ghezzehei and Or, 2000) and this welding is thought to increase soil strength and restrict root growth in irrigated soils (Cockroft and Olsson, 2000).

This chapter will review soil structure and strength and the factors controlling them, the significance of soil strength for root growth and processes of structural degradation including the rather limited literature about aggregate coalescence. In the subsequent chapters, a number of experiments will be described which were designed to investigate factors affecting aggregate coalescence and its effect on the early growth of tomato plants. At the end of the thesis the results of these experiments are discussed and general conclusions are drawn.

1.2. Literature Review

1.2.1. Soil Structure

Definitions of soil structure have mainly focused on the arrangement of soil particles and the spaces surrounding them. This was expressed by Marshall and Holmes (1978) as "the arrangement of the solid phase of the soil and of the pore space located between its constituent particles". This includes the size, shape and arrangement of the aggregates formed where primary particles are clustered together into larger separate units (Marshall *et al.*, 1996). However, Dexter (1988) defines soil structure as "the spatial heterogeneity of different components or properties of soil". Thus, this definition appears to encompass all aspects of soil structure that affect root growth including soil strength.

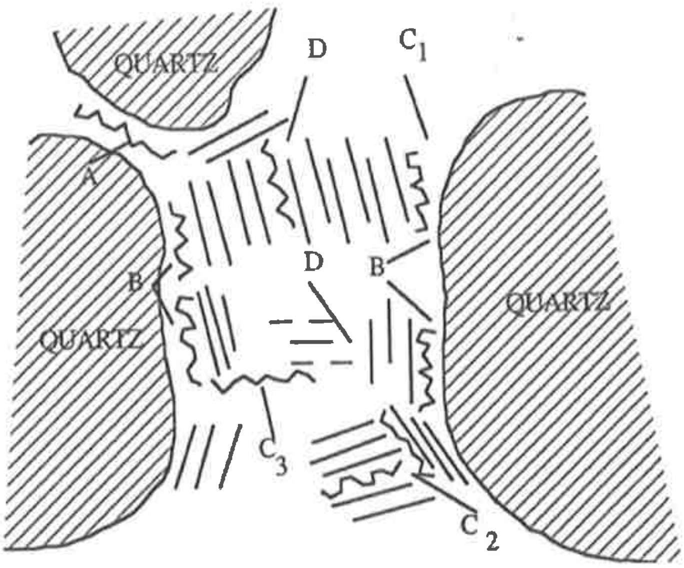

Figure 1.1. A model of a soil crumb: A=quartz-organic matter-quartz; B=quartz-organic matter-clay domain; C=Clay domain-organic matter-clay domain (C_1=face-face; C_2=edge-face; C_3=edge-edge); D=clay domain-clay domain (From Emerson, 1959).

Soil structure encompasses a very wide scale ranging from 10^{-9} to 10^{0} m (Kay, 1990; Oades, 1993). This broad range of scales has lead some authors to consider various hierarchies within soil structure. Tisdall and Oades (1982) initiated a conceptual model of soil hierarchy which was later developed by Hadas (1987). This concept describes how the material of a lower hierarchical level may act as cementing or binding agents between soil materials of a higher order. A model of soil crumbs (Figure 1.1.) proposed by Emerson (1959) is still relevant to this concept. The model clearly shows the presence of hierarchy in a soil crumb (aggregate). At the lowest level of the hierarchy, single particles cluster together (Dexter, 1988) into a separate unit known as a domain of oriented clays or organic matter (Emerson, 1959). In the next level the clay domains link quartz particles while organic matter links the clay domains with the quartz or directly links the quartz particles. These linkages form microaggregates and further macroaggregates through combination and fragmentation processes (Dexter, 1988).

Table 1.1. Soil structural organisation and the mechanisms causing instability of structural units in water (From Rengasamy, 1984a)

Structural units	Average size (μm)	Pore size (μm)	Pore function	Mechanism causing aggregate instability
Platelets (unit layer)	0.002	<0.002 (inter layer)	Bound water (inter-layer)	Swelling (adsorption of water)
Clay crystals and quasi crystals	0.05	0.005 (inter-crystalline)	Bound water	Crystalline swelling (limited) Dispersion of platelets
Domains	1-2	0.1 (inter-domain)	Bound water Available water Micro-organisms Aeration (limited)	Very limited swelling Dispersion of clay crystals and quasi crystals
Micro-aggregates	2-250	50	Available water Aeration Root growth Slow drainage Micro-organisms	Slaking due to -breaking of organic bonding in loamy soils -differential swelling pressure Dispersion of domains
Macro-aggregates	250-2000	1000 (inter-aggregates)	Fast drainage Earth worms Root growth	
Clods	>2000	Cracks and fissure (undefined)	Fast drainage	Swelling and shrinking Dispersion within clod matrix

The hierarchy is also embodied in a classification of soil structural organisation involving clay particles discussed by Rengasamy *et al.* (1984a). This structural organisation is classified into different structural units according to their sizes (Table 1.1). Various sizes of pores exist within these structural units performing different functions of agricultural importance, and involving different mechanisms in destabilising these various structural units.

1.2.2. Factors controlling soil structural stability and strength

Soil structure is a transient property, which can be altered by different processes including wetting/drying, freezing/thawing, shrinking/swelling, physical disturbances associated with equipment, animals, roots and organic matter (Aluko and Koolen, 2000). As soil structural stability is strongly related to the stability of aggregates that form the soil, the following text will review the effect of the different processes on aggregate stability.

Wetting and Drying

Wetting and drying are two of the most important natural processes that may cause substantial disruption of soil aggregates. However, as most changes occur during wetting, the following review deals mainly with wetting. Wetting leads to a process called slaking. It refers to the breakdown of large aggregates into smaller ones as the aggregates are suddenly immersed in water (Chan and Mullins, 1994). It occurs when disruptive forces such as differential swelling, compression of trapped air and heat of wetting are stronger than the forces of aggregate stabilisation as dry aggregates are wetted rapidly (Emerson, 1967; Emerson, 1977; Collis –George and Lal, 1971; Chan and Mullins, 1994). Slaking causes the collapse of large pores and denser packing of soil aggregates (Mullins *et al.*, 1990) leading to poor soil permeability and aeration (Agassi *et al.*, 1981) and high strength (Mullins *et al.*, 1990).

Initial water content may affect the extent to which soil aggregates slake. Using different soils from Australia and Britain, Chan and Mullins (1994) found that after wetting, the proportion of aggregates >250 μm tended to be higher when the initial matric suction was less than 10 kPa which indicated that the soils slaked more if the initial suction was greater than 10 kPa. This result was consistent with an earlier study by Panabokke and Quirk (1957) in which they found that with initial matric suctions between 1 and

10 kPa, soils tended to be more stable than at initial matric suctions of more than 10 kPa. The effect of wetting may be different between different sizes of aggregates. Using seedbeds in a laboratory based experiment, Bresson and Moran (1995) found that in seedbeds having coarse aggregate size distribution (no aggregates < 500 μm), coalescence occurs at the bottom of the seedbeds where rapid wetting occurs, while in fine seedbeds aggregates of <500 μm agglomerated throughout the samples.

The way soils are wetted also plays an important role in the breakdown of aggregates. In laboratory experiments, Gusli *et al.* (1994a) found that flood-wetting of aggregate beds leads to greater structural collapse compared to tension wetting. The greatest impact of these methods of wetting is probably via their greatly different rates of wetting of soil aggregates which lead to vastly different degrees of air entrapment. In flood wetting, the collapse was associated with the following processes: (i) aggregate comminution controlled by water suction and aggregate stability and (ii) comminuted aggregates consolidated on draining which was controlled by effective stress. These processes eventually caused shrinkage in bed volume (Gusli *et al.*, 1994a).

The effect of wetting and drying on aggregate stability has been widely studied although inconsistent results have been observed. Utomo and Dexter (1982) found that wetting and drying could both increase and decrease aggregate stability in the same soils. To explain this phenomenon, they introduced the concept of equilibrium proportion or range of proportions of water stable aggregates. For a given composition and environment history, soil which has less than the appropriate equilibrium value will increase its proportion, and soil which has more than the appropriate value will decrease its proportion. Later studies showed that clay types appear to affect aggregate stability after wetting and drying. Singer *et al.* (1992) found that sand-kaolinite aggregates were more stable than sand-illite/smectite. In another study, Piccolo *et al.* (1997) observed that aggregates dominated by kaolinite were more stable than those dominated by illite or smectite after several wetting and drying cycles.

Freezing and Thawing

Other natural processes that have a major impact on soil structure and its stabilisation are freezing and thawing. According to Nagasawa and Umeda, (1985), the size of ice crystals controls the size and stability of aggregates. Some large crystals created by slow freezing may form large stable aggregates while rapid freezing forms small ice crystals and smaller aggregates (Harris *et al.*, 1966). The redistribution of water as a result of freezing processes may cause porosity to disappear in some zones and new pores to be formed in others (Kay, 1990). Furthermore, Kay (1990) stated that a large increase in porosity could occur in the frozen zone where water is accumulated.

Swelling and Shrinking

Swelling and shrinking is one of the major factors affecting soil structure. Soil shrinkage, used to reflect this property, is defined as the specific volume change of soil relative to its water content in which two stages of shrinkage can be recognized, normal shrinkage in which the volume change is equal to the change in water content and residual shrinkage in which the volume change is less than the change in water content (Haines, 1923).

Swelling and shrinking greatly affect soil hydraulic properties. Swelling during wetting reduces soil pore size and may decrease hydraulic conductivity, especially when accompanied by dispersion (Frenkel *et al.*, 1978). Shrinking during drying generates cracks delineating aggregates and creating zones of preferential water flow. In a recurring crack pattern the water will continue to infiltrate into specific areas of the soil via the cracks thus bypassing much of the soil matrix. In an alternating crack pattern the water will not bypass nearly as much of the soil matrix and the overall wetting with time will be more uniform. (Wells *et al.*, 2003). Swelling also promotes incipient failure of dry aggregates during wetting under suction (Quirk and Panabokke, 1962) or slaking during rapid wetting (Emerson and Greenland, 1991).

Tillage

The obvious example of physical disturbance caused by human activities is tillage. During tillage, the use of various types of equipment causes shearing, compression or tension leading to changes in both porosity and pore size distribution. The largest pores disappear first as the distance between aggregates decreases resulting in the aggregates flattening at their contact points (Kay, 1990; Kataou *et al.*, 1987 and Braunack *et al.*, 1979).

Organic Matter and Soil Structural Stability

Organic matter only comprises a small proportion (1-5%) of mineral soil, but it plays a very important role in the stabilisation of soil aggregates. Soil organic matter is defined as 'the total of all biologically derived organic matter residing within the soil matrix and directly on the soil surface including thermally altered materials' (Baldock and Skjemstad, 2000; Baldock and Nelson, 1999). Table 1.2 presents the various components of soil organic matter.

Table 1.2. The various components of soil organic matter (From Baldock and Skjemstad, 2000)

Component	Definition
Living components	Organic materials associated with the tissues and cells of living plants, soil microorganisms and soil fauna
Non living components	
Dissolved organic matter	Water soluble organic materials that are <0.45 μm
Particulate organic matter	Organic fragments with a recognisable cellular structure derived from any source but usually dominated by plant derived materials
Humus	A mixture of amorphous organic materials containing identifiable biomolecules (polysaccharides, protein, lipids, etc) and non identifiable molecules (e.g. humic substances)
Inert organic matter	Highly carbonised organic materials including charcoal, charred plant residues, graphite, and coal

At a large scale, plant roots and fungi protect macroaggregates from breaking down. Roots modify soil structure by pressing, ramifying, separating, compressing, and incorporating within soil particles or aggregates (Marshall and Holmes, 1988). Growing roots release various kinds of compounds such as mucilages containing polysaccharides that can bind microaggregates through different mechanisms (Oades, 1978; Tisdall and Oades, 1982). Fungi through their hyphae can form stable macro aggregates (Tisdall, 1991) as a result of the reorganisation of mineral particles into aggregates (i.e. aggregate initiation) and the stabilisation of these aggregates by physical and chemical processes through cementation by extracellular polysaccharides (Chenu, 1989).

The important role of microorganisms is due either to their ability to mechanically hold soil particles together (Lynch and Brag, 1985) or to produce exudates of polysaccharides that are able to stabilise micro aggregates (Tisdall, 1991). The stability of these micro aggregates arises from the fact that the polysaccharide acts as a glue binding the aggregates together (Chesire, 1979; Martin 1971).

The effect of organic matter on aggregate stability may last for only a few weeks to several years. Tisdall and Oades (1982) classified the effect of organic binding agents into three categories: (i) transient; only polysaccharides, (ii) temporary; roots and fungal hyphae, and (iii) persistent; resistant aromatic components associated with polyvalent metal cations and strongly sorbed polymers.

In general, increasing organic matter content in soil may also increase the water holding capacity as a result of the porous characteristic of organic matter in influencing the distribution of pore size and water retention characteristic (Nelson, 1997).

Chemical agents

Chemical factors affect soil structure by controlling processes related to clay particle activities such as swelling and dispersion. Swelling takes place during the adsorption of water by hydrated cations involved in electrostatic bonding between clay particles. With increasing water content, the distance between the particles progressively increases to more than 7 nm resulting in clay particles becoming independent of each other (Rengasamy and Olsson, 1991). This process leads to dispersion in which clay particles are individually released from aggregates causing adverse soil conditions for root growth such as low permeability, poor aeration, high bulk density and strength as the soil dries. The factors controlling swelling and dispersion are basically the same (Rengasamy *et al.*, 1984b) including the amount, size, mineralogy and surface charge characteristics of the clay fractions, exchangeable cations, the concentration and composition of electrolytes in soil solution, soil pH, organic matter and poorly soluble inorganic salts (Emerson, 1977; Quirk and Schofield, 1955; Rengasamy *et al.*, 1984b; Shainberg and Letey, 1984).

The dispersibility of clay with sodium as the major adsorbed cation can be controlled by maintaining the appropriate electrolyte level in irrigation water (Quirk and Schofield, 1955). According to Rengasamy and Olsson (1991) soil with an exchangeable sodium percentage (ESP) >6 and electrolyte concentration (EC) below the threshold electrolyte concentration (TEC) disperse spontaneously. The value of TEC, however, varies from soil to soil and could only be predicted with empirical tests, even for soils with similar clay type and content. The TEC necessary to prevent clay dispersion can be changed by factors affecting the negative charge in soil. Using Figure 1.2, Rengasamy and Olsson (1991) illustrated how the negative charge in soil changes the activity of clays. For a given sodium adsorption ratio (SAR), the line A-B represents the TEC needed to prevent spontaneous clay dispersion. However, with increasing negative charge, the slope and intercept of the line A-B relating SAR and EC increase to become the line C-D (Figure1.2). Factors affecting negative charge for a given soil include pH, broken bonds of organic and bio-polymers, adsorbed organic molecules and exposure of particle surfaces due to fragmentation of aggregates (Rengasamy and Olsson, 1991).

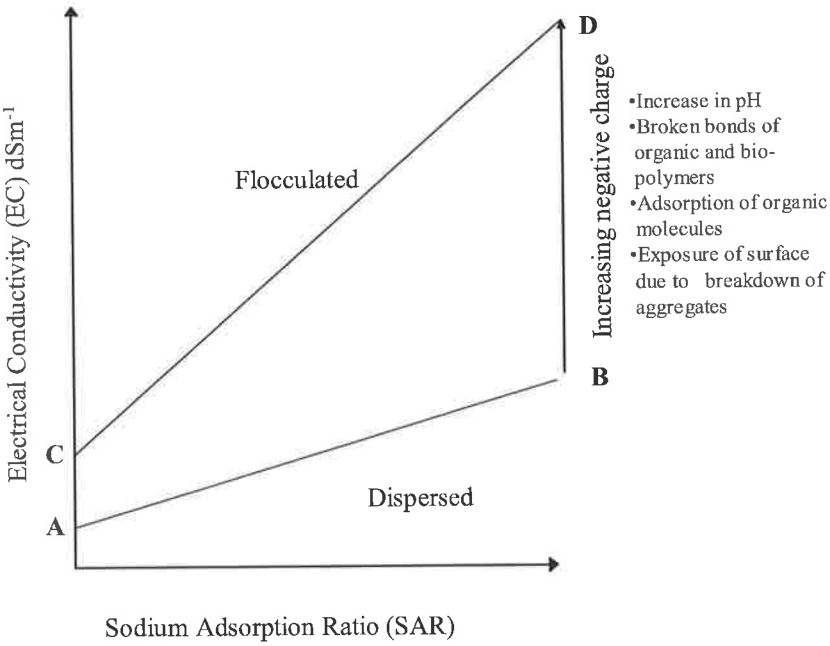

Figure 1.2. Factors influencing threshold electrolyte concentration (From Rengasamy and Olsson, 1991)

The dominant type of clay mineral in soil determines the effect of exchangeable cations and electrolyte in increasing swelling and dispersion in aggregates. Illite is more sensitive to dispersion than smectite or montmorillonite clay minerals due to its different size and shape and lower strength of edge-face attraction (Greene *et al.*, 1978; Oster *et al.*, 1980). However, under conditions where salinity is negligible, the dispersion at a given ESP has been observed to be montmorillonite>halloysite>mica (Velasco-Molina *et al.*, 1971; Frenkel *et al.*, 1978)

The extent of clay dispersion may be minimised by the presence of binding agents such as aluminium/iron oxides, calcium or soil conditioners. The role of aluminium and iron oxides was found to be important as binding agents in prairie soils and lateritic soils (Oades, 1963; Deshpande *et al.*, 1968). Calcium in the form of gypsum and phosphogypsum has been widely used to mitigate clay dispersion in sodic soils (Marshall and Holmes, 1988; Kazman *et al.*, 1983). Polyvinyl alcohol (PVA) is one of the many soil conditioners that has been extensively used to improve aggregate stability (Emerson and Raupach, 1964; Oades, 1976; Stefanson, 1974; Cruse and Larson, 1977; Sojka and Lentz, 1994).

Effective Stress

The term "soil strength" refers to the capacity of a soil body to withstand forces applied to it without experiencing deformation, whether by rupture, fragmentation, or flow (Hillel, 1998). The magnitude of soil strength derives from inter-aggregate bonds and intra-aggregate bonds (Aluko and Koolen, 2000) produced by cohesive forces between particles/aggregates and internal friction generated by particles/aggregates (Marshall and Holmes, 1988).

A number of factors have been related to soil strength including water content, texture, bulk density and organic matter. It is difficult to separate these effects as they can interact with each other in a way that one factor may prevail over the others. However, the following discussion will attempt to treat them separately.

In general, soil strength is largely dependent upon water content or matric suction; soil strength increases with decreasing water content or increasing matric suction. Water contributes to soil strength through its ability to influence forces of cohesion and surface tension producing additional intergranular pressures which is called effective stress (Jennings, 1961). Under unsaturated conditions the effective stress within a soil progressively increases along with increasing water suction reaching a maximum at a certain suction beyond that of air entry and causing a reduction in the shear plane fraction (Marshall and Holmes, 1988) in which water no longer contributes to increase in soil strength.

The development of effective stress in unsaturated soil is described by Mullins and Panayiotopolous (1984) with the following equation

$$\sigma' = \sigma + \chi\psi \qquad (2)$$

where σ' is the effective stress, σ is the normal stress, ψ is the matric suction and χ is a function of the degree of saturation having values between 0 (dry soil) and 1 (saturated soil) (Mitchell, 1993). Using a blend of coarse and fine sand and kaolin, Mullins and Panayiotopoulos (1984) found that increasing matric suction from 100 to 1000 kPa could dramatically increase soil strength. In another study, Kemper and Rosenau (1984) observed that soil with a large amount of silt had higher strength at intermediate water content predominantly because of greater effective stress at this water content whereas soil with a low amount of silt but a large quantity of clay had strength not only generated by the effective stress but also by other mechanisms such as selective precipitation of silica, $CaCO_3$, and other slightly soluble solutes acting as binding agents (Kemper and Rosenau, 1984).

Texture

The role of texture in soil strength may be via its effect on either frictional or cohesive forces. Soil consisting of coarse particles has its strength primarily associated with frictional rather than cohesive forces whereas in fine-textured soil, strength mainly arises from cohesive forces. Soil with a high content of sand particles tends to have higher penetration resistances than clay soil. Smith *et al.* (1997) found that sandy soil might have a penetrometer resistance value of 0.64 MPa compared to 0.49 MPa for clay soils when those soils were compacted to a bulk density of 1.39 and 1.37 g cm^{-3}, respectively, using a proctor cylinder. This result was consistent with Spivey (1986) who studied soil resistance in a wide variety of soil textures. At a bulk density of 1.6 g cm^{-3}, soils containing >70% sand particles had probe resistances higher than 4.5 MPa while those containing >30 % clay tended to have probe resistances less than 1 MPa.

Bulk Density

However, at constant bulk density, increasing clay content may increase soil strength as a result of larger contact areas. Smith *et al.* (1997) found that at constant water potential (-1500 kPa), soil penetrometer resistance increased with increasing clay content, reaching its maximum when the clay content was approximately 45%. Greacen (1981) found that a much higher clay content in the B horizon caused this horizon to have higher soil penetrometer resistance

(2.2 MPa) than A horizon (1 MPa) although the bulk densities of the two horizons were very similar (1.5 g cm^{-3}).

Increasing bulk density tends to increase soil strength due to higher contact area between particles/aggregates. Using cone penetrometer resistance as an index for soil strength measurement of a silt loam, Wells and Treesuwan (1978) found that at moisture contents of approximately 20%, soil strength increased from 5 to 8 MPa when bulk density increased from 1.15 to 1.23 g cm^{-3}. A similar result was also shown by Ley *et al.* (1995), who found that bulk densities increasing from 1.17 to 1.63 g cm^{-3} resulted in soil strengths increasing from 0.73 to 7.52 MPa. Various bulk densities created by applying different degrees of compaction to a sandy loam soil were found to result in a significant relationship between bulk density and soil strength (Smith *et al.*, 1997). However, the relationship between bulk density and soil strength might be very poor as bulk density values are merely a ratio of soil mass to total soil volume and do not take into consideration the arrangement/bonds of particles/aggregates within a given soil volume (Horn *et al.*, 1994)

Organic Matter and Soil Strength

The impact of organic matter on soil strength may vary depending on soil texture and organic matter type. Organic matter tends to increase the strength of sandy soils but not of clay soils. Sojka *et al.* (1991) studied the effect of organic matter on soil strength in sandy loams and found that soil resistance increased with a gradual increase in organic matter in soil that had a history of conservation tillage. Using a similar soil texture, Ekwue (1990) also found that grass addition could result in soil resistance increase from 19 to 24 kPa but that soil resistance was reduced to 12 kPa when peat was added. Zang *et al.* (1997) found that soil resistance of a sandy soil increased from 0.64 to 1.08 MPa when this soil was added with slightly humified peat and compacted to bulk density of 1.6 g cm^{-3} but with clay soils the resistance was reduced from 0.49 to 0.30 MPa. These differing observations of soil resistance in relation to texture may arise from the different roles of organic matter in soil of different textures. The main effect of organic matter on reducing soil strength may be related to its ability to disrupt surface tension forces (Causarano, 1993).

1.2.3. Requirements for plant growth

The importance of soil structure in relation to plant growth can be viewed from the ability of the plant roots to explore the soil for water and nutrients with relative ease. For plants to grow successfully good soil structure may vary from one species to another and different stages of root growth may also need different soil structure. However, in general an open soil structure is considered to be a favourable rooting medium for plants since it provides large pores, favours high infiltration rates, better aeration, and offers less resistance to rupture (Kemper and Rosenau, 1984). Good soil structure should have sufficient pores for water storage available to plants as well as pores for transmission of water and air and pores in which roots can grow (Oades, 1984).

Letey (1985) introduced the concept of non-limiting water range (NLWR) for assessing soil structural quality based on the relationship between water content, aeration and mechanical impedance in soil. Figure 1.3 illustrates the availability of water for plant growth is restricted by poor oxygen diffusion rate at the wet end (field capacity) and by mechanical resistance at the dry end (permanent wilting point). The concept of NLWR was later developed into least limiting water range (LLWR) by da Silva *et al.* (1994). The LLWR is defined as the range in soil water content after rapid drainage has stopped within which limitations to plant growth associated with water potential, aeration, and mechanical impedance to root penetration are minimal (da Silva and Kay, 1997). Plant growth in soils with a narrow LLWR is more susceptible to drought and high precipitation than that in a wide LLWR (Kay, 1989).

On the one hand, to maintain the "ideal" soil structure, aggregates that form macropores have to be stable and sufficiently strong against any deformation forces (such as wetting and drying, rainfall impact or tillage) otherwise, these macropores may collapse. On the other hand, the strength of these aggregates should not be too high in order to allow roots to grow relatively unobstructed. Penetration values of less than 0.75 MPa are considered to offer relatively unimpeded root growth (Mullins *et al.*, 1990).

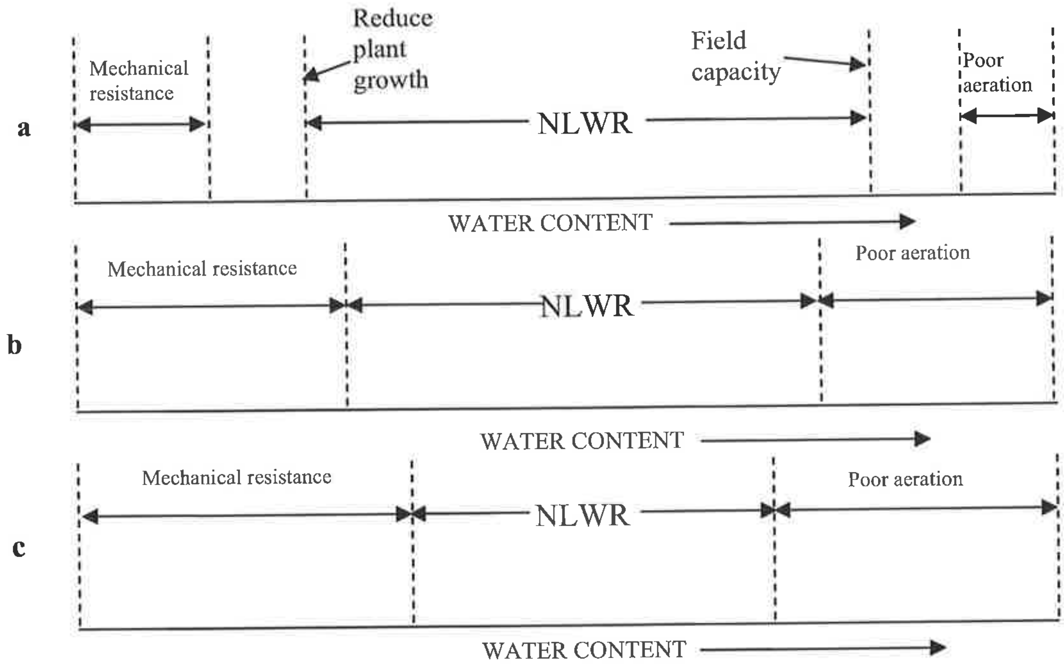

Figure 1.3. Schematic representation of the relationships between soil water, aeration and mechanical resistance in soils with increasing bulk density and increasing structural degradation in going from case a to c (From Letey, 1985).

The relative absence of slaking and dispersion (Cockroft and Olsson, 2000) and minimal bulk density changes (Grant *et al.*, 2001) in soil with coalesced aggregates to some extent indicates good soil structure. Furthermore, according to Cockroft and Olsson (2000) in this kind of soil structure large pores may be maintained. Therefore, the only limitation for root growth associated with low crop yield in such soils would appear to be high soil strength. However, the contrast in physical characteristics between coalesced and uncoalesced soil was very large. Bulk density and penetration resistance of the coalesced soil was found to be 1.4 g cm^{-3} and 2.3 MPa, respectively, compared to only 0.8 g cm^{-3} and 0.8 MPa, respectively, for the uncoalesced soil (Cockroft and Olsson, 2000) indicating that slaking or dispersion might have taken place.

1.2.4. Significance of soil strength for root growth

Most studies of the effect of soil strength on root growth have been conducted on soils that had unstable aggregates where compaction, slaking and dispersion are the common processes (*e.g.* Boone *et al.,* 1978). But there is a lack of information available on how plant roots might respond to a condition where all other soil physical characteristics seem to favour root growth except soil strength. This phenomenon known as coalescence seems to have detrimental impact on plant yield (Cockroft and Olsson, 2000) and it is widely known that plant roots have the capability to sense mechanical impedance in soils without causing restrictions to their growth but send a signal to the above ground part of the plant that may induce stomatal closure (Masle, 1999). This situation may lead to a reduction in the rate of photosynthesis and as a consequence, plant yield is reduced. The following text, therefore, only reviews the effect of soil strength on roots resulting from other processes of structural degradation.

Roots grow in a soil either by entering soil macropores equal to or larger than their diameter or by deforming the surrounding soil. In the latter case, the soil mechanical resistance directly influences root growth in which the roots must exert a growth pressure exceeding the soil resistance in order to displace soil particles, overcome friction and elongate through the soil. The relationship between the rate of root elongation and the soil resistance, when water is not a limiting factor, has been described by Greacen and Oh (1972) as:

$$R = m \, [\, P - W_c - \sigma]$$

Where R is the elongation rate, m is the extensibility coefficient of the cell wall, P is the turgor pressure, W_c is the cell wall yield threshold and σ is the soil resistance (or growth pressure).

Due to experimental difficulties in directly measuring root resistance, most studies on root growth resistance have been indirect ones (Bengough and Mullins, 1990) and the best indirect method of estimating resistance to root growth through soil involves measuring soil resistance to penetration. Most penetrometers consist of a conical head on a cylindrical shaft, which is pushed through the soil at a slow constant rate. The following equation can be used to calculate root growth pressure (σ):

$$\sigma = q_p / (1 + \mu \cot \alpha),$$

where q_p is the penetrometer resistance, μ is the coefficient of soil-metal friction and α is the penetrometer cone semi-angle (Clark *et al.*, 2003). Bengough and Mullins (1991) reported that the above equation gave estimates of σ that were similar to their direct measurements obtained by growing roots into cores of soil on a balance.

The external morphology of roots can be used to diagnose the high soil resistances that roots are encountering (Bennie, 1991). Root thickening is a common feature of high soil resistance (*e.g.* Materechera *et al.* 1991, Bengough and Mullins, 1991). Such increase in root diameter may reduce the resistance at the root tip, and by this mechanism roots are able to further elongate (Abdalla *et al.*, 1969).

The rate of root elongation has been found to decrease approximately exponentially with increase in soil strength irrespective of plant types (e.g. Bengough and Mullins, 1990; Goss and Russel, 1980; Taylor and Gardner, 1963). In a calcareous soil with coarse loamy texture, artificial compaction, achieved by driving a heavy tractor over an entire experimental area leading to cone penetration resistance of approximately 2.9 MPa, greatly restricted root growth to less than 60 cm depth compared to 80 cm when there was no compaction (Boone *et al.*, 1978). A tap root length of soybean decreased from more than 4.5 cm to less than 2 cm when compaction caused cone penetration resistance to increase from 0.4 MPa to 2 MPa (Khalilian *et al.,* 1990). However, in coarser textures, much lower cone penetration resistance was observed to reduce root length. Bengough and Mullins (1990) found that in cores of two sandy loams with cone penetration resistances of 0.39 and 0.48 MPa, the rates of maize root elongation were reduced to between 50 and 90 %, respectively, of that of control plants grown in soil of relatively low cone penetration resistance.

Greater lateral root formation is also another sign of restriction (Goss and Russel, 1980; Goss, 1977). In a fine sandy loam, a reduction of root numbers ranging from 40 to 68 % was found when roots of six different species encountered a compacted layer with a penetrometer resistance of 3.0 MPa (Materechera *et al.,* 1992).

The maximum soil penetration resistances that roots can cope with before any signs of soil impedance appear, vary with plant type and growing stage. Despite this Mullins *et al.*, (1990) have assigned a range of penetration values for the ease of root penetration in hardsetting soil. Penetration resistances (MPa) of less than 0.75 were considered relatively unimpeded; 0.75-1.5 posed significant impedance; 1.5-3 posed substantial/serious impedance; 3-6 allowed little or no growth and more than 6 was impenetrable. These values were not determined in correspondence with root growth observations.

1.2.5. Soil coalescence: another process of soil structural degradation?

A number of processes have been associated with structural degradation which causes restriction to root growth. These include compaction, crusting, and aggregate coalescence. Apart from aggregate coalescence, all other processes of structural degradation involve compaction, slaking or dispersion causing high soil strength accompanied with a significant increase in bulk density. The soil structural problem in aggregate coalescence, however, appears to be different since the increases in soil strength may not necessarily be accompanied by significant increases in bulk density as slaking and dispersion are relatively absent (Cockroft and Olsson, 2000; Grant *et al.*, 2001). As the other forms of structural degradation have been discussed elsewhere, the following text is only related to aggregate coalescence obtained from the limited published literature.

The term coalescence has been used in several studies to describe a soil structural condition such that the soil aggregates are joined at their points of contacts due to their plastic behaviour (Bresson and Moran, 1995; Ghezzehei and Or, 2000). Deformation occurs when the applied stress is larger than the shear strength of the soil causing large localised stresses which induces flattening at the contact points of the aggregates (Day and Holmgren, 1952). This flattening causes the soil aggregates to coalesce. Cockroft and Olsen

(2000) described the term coalescence as a distinct form of soil structure degradation that is not due to compaction, slaking, or dispersion. Their field observations indicated that water-stable and non-trafficked soil became hard. Even though some biopores still exist that might maintain good hydraulic conductivity and drainage, the hard matrix caused the root growth and activity to be substantially reduced compared with roots in loose soil and this reduces crop yield. They suggested that this phenomenon is one of the reasons for low productivity in zero and minimum tillage soil management regimes.

The dynamic process of coalescence is analogous to the glass sintering process. Or (1996) proposed the analogy based on: (i) the similarity of the high temperature effect on glass powder with wetting in soils which decrease soil strength and (ii) the major driving forces in both systems are the capillary forces. Furthermore, Ghezzehei and Or (2000) developed a geometrical model for soil aggregate coalescence (Figure 1.4) based on the physical process that requires no formal analogy with liquid-phase sintering.

The progress of aggregate coalescence can be viewed from soil strain-based conditions. Using non-swelling soil, Ghezzehei and Or (2000) defined the onset and termination of aggregate coalescence in term of positive strain rate given by:

$$\sigma \frac{\partial SA_{LV}}{\partial h} \geq 4\sqrt{2}\pi a^2 \tau_y$$

where σ is surface tension of liquid water at 20C (0.07294 Nm^{-1}), SA_{LV} is surface area of liquid-vapor interface (m^2), h is axial strain (m), a is the aggregate radius and τ_y is the bulk shear strength of the soil (Pa). During drying of initially wet soil, aggregate deformation (coalescence) commences when the capillary forces (left-hand side) exceed the yield stress (soil strength, right-hand side). The deformation ceases at a certain matric potential when soil strength exceeds the available capillary energy.

Using a unit cell of soil consisting of equal-sized spherical aggregates in cubic packing as a basic element to illustrate the application of the geometrical model (Figure 1.4), Ghezzehei and Or (2000) stated that the matric potential range that can support the capillary liquid for aggregate coalescence to occur is bound by lower and upper limits. The lower limit corresponds to a condition where the liquid-vapour interface with radius of the liquid neck (r) equal to that of the solid neck (*p*). The upper limit is associated with the largest liquid-neck radius (r) before the liquid-vapour interfaces touch its neighbour. Two scenarios were considered in relation to this range of matric potential supporting aggregate coalescence; (i) under constant matric potential conditions and (ii) for a linear drying rate (wetting and drying cycles) (Ghezzehei and Or, 2000).

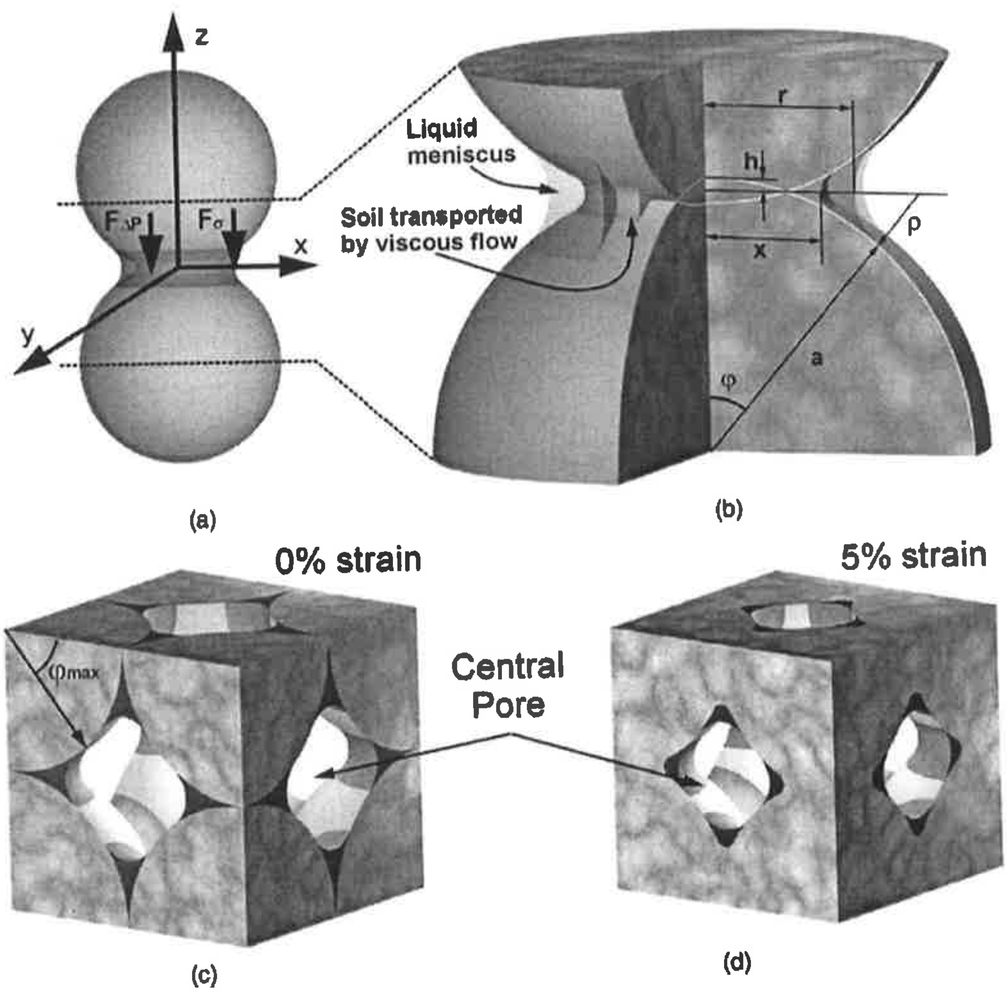

Figure. 1.4. The basic geometrical model for aggregate coalescence: (a) a pair of equal-sized aggregates in a 3D Cartesian coordinate system, and tensile forces acting along the contact area; (b) definition of basic geometric variables in a cross-section. Cubic packing (c) before and (d) after coalescence (From Or and Ghezzehei, 2002).

According to Ghezzehei and Or (2000) the range of matric potentials that supports capillary menisci in the interaggregate pore space for aggregate coalescence is dependent upon the size of aggregates. The range of matric potential for smaller aggregates is lower than that for larger aggregates, thus, during a given drying process smaller aggregates coalesce later than larger ones.

As the model of aggregate coalescence presented by Ghezzehei and Or (2000) only uses strain to denote the changes in soil structure, it is not obvious how soil bulk density and soil strength develop as aggregate coalescence progresses with time. These two properties are very important from the point of view of root growth.

1.3. Aims

From the literature review, a number of factors appear to affect aggregate coalescence. A low matric suction during wetting can cause structural changes of water stable aggregates due to their plastic behaviour. Repeated wetting and draining processes may increase the impact of aggregate coalescence on soil strength as these processes could strengthen the bonds between aggregates possibly through age hardening. Soil at lower depth consolidates more due to the effect of overburden suggesting that the same effect may also occur for aggregate coalescence. Aggregate size affects coalescence because it determines the number of contacts between aggregates per unit volume of soil. Wetting rate is an important factor for aggregate coalescence as it can have an effect on the rate of material exchanges at the point of contacts between aggregates that cause aggregates to coalesce. The use of soil conditioner such as polyvinyl alcohol (PVA) may provide either more stability to soil aggregates or coatings aggregate exteriors thus minimising material exchanges at the point of contact between them. Sodicity may affect aggregate coalescence as it controls the extent of dispersion, creating more or stronger contact areas for aggregates to coalesce. As aggregate coalescence may result in high soil resistance, root growth in such soil may be restricted.

Based on these factors thought to affect aggregate coalescence, the present study had the following two objectives: (i) to identify the effects of matric suction, repeated wetting and draining cycles, overburden, aggregate size, wetting rate and PVA, and sodicity on aggregate coalescence and (ii) to determine the effect of aggregate coalescence on the early stages of tomato growth.

Chapter 2: Materials and General Methods

2.1. Soil samples

Six surface soil samples (0-10 cm) were used in this project. Shepparton fine sandy loam (Skene and Poutsma, 1962) is a red-brown earth from the Goulburn Valley of south-eastern Australia (Rengasamy, 1983). Red- brown earths are widespread in Southern Australia and are extensively irrigated for pasture and for horticultural and viticultural production, particularly in New South Wales, Victoria and South Australia. Williams (1981) and Cockroft and Martin (1981) have identified them as the most important irrigated soil in Australia. The cultivated Shepparton soil sample came from an irrigated orchard with no tillage and the virgin soil sample was taken from an adjacent, grassed area beneath a 50-year-old fence (Cockroft and Olsson, 2000). Cornella clay is a self-mulching, heavy grey clay taken from Rochester in south-eastern Australia (Skene and Harford, 1964; Grant *et al.*, 2001). The cultivated Cornella soil had been used for intensive cropping (cereal, maize and tomato) for more than 50 years whereas the virgin Cornella soil was under native vegetation (Grant *et al.*, 2001). Wiesenboden soil is a virgin, self-mulching black earth collected from the Waite Agricultural Research Institute (Barzegar *et al.*, 1995; Schafer and Singer, 1976). Rhynie soil is a cultivated, self-mulching black earth from the mid-North region of South Australia (Grant and Blackmore, 1991). Rhynie and Wiesenboden soils were included in this research in order to investigate how variations in soil mineralogy may affect aggregate coalescence. However, because of time constraints and the availability of sufficient sample, use of the Rhynie soil was confined it to the sodicity experiment described in Chapter 8.

Some properties of the soils are presented in Table 2.1.

Table 2.1. Selected properties of soils

Soil	OC	CEC	θ_m**	$pH_{1:5}$	$EC_{1:5}$	Particle size (%)			Mineralogy
	%	cmol(+)kg^{-1}	%		dS/m	clay	silt	sand	
Shepparton (c)	1.5	24.2	3.4	6.5	0.06	17.5	15	67.5	M*, K*, S$^{\#}$
Shepparton (v)	2.8	27.0	2.9	6.1	0.05	11.3	11.2	77.5	
Cornella (c)	1.2	57.4	7.5	6.7	0.37	57.5	11.3	31.2	Mt*, RIM*
Cornella (v)	3.7	48.8	5.8	6.5	0.25	36.3	15	48.7	
Rhynie	0.9	82.8	8.2	6.6	0.15	61	10	29	S*, RIM*
Wiesenboden	3.5	40.7	10.4	6.9	0.13	55	26	19	RIM*, I$^{\#}$

K=Kaolinite; M=Mica; Mt=Montmorillonite S=Smectite; RIM=Randomly interstratified minerals; I=Illite
** and $^{\#}$ =major and minor mineral*
***gravimetric air-dried water content under laboratory conditions*

The soils were air dried and sieved to retrieve various aggregate size fractions ranging from <0.5 to 4 mm. For soil physical measurements, aggregates were packed by pouring them through a funnel moving in a circular fashion into cylindrical rings 4.77 cm i.d. and 5 cm high ("soil cores") with a thin mesh at the base, and the rings then gently tapped until the soil aggregates settled before experiments were conducted.

2.2. Wetting and draining of soil cores

Initial wetting near saturation was chosen as the most practical approach in most of the experiments in this project partly because of the large number of soil cores involved. Although slow wetting is more effective in minimising slaking and dispersion and their consequent interference with the process of aggregate coalescence, conventional wetting under suction was extremely slow. Under suction, the wetting process was limited to points of inter-aggregate contact, usually in the absence of fine material and the use of thin mesh at the base of the soil cores also contributed to the wetting being even slower. At 1 kPa suction at least 12 and 48 hrs, respectively were needed to wet the cultivated Shepparton and Cornella soil cores while the virgin Shepparton soil failed to wet even after one month (Chapter 3). As a consequence of rapid wetting, measurements of penetration resistances a few millimetres from the base of the soil cores were not included due to severe structural damage and edge effects.

Near Saturation wetting

In general, wetting near saturation was conducted by placing the soil cores in a beaker containing free water at a level 10 mm above the base of the soil cores. This provided a matric potential ranging from +0.1 kPa at the base of the core to –0.4 kPa at the top and allowed the soil to wet by capillary rise in which relatively faster wetting occurred at the bottom than at the top (Figure 2.1). Wetting was allowed to continue for either 24 or 48 h before the cores were drained.

Suction wetting

Wetting under suction was conducted by placing soil cores on sintered glass funnels (porosity 4; 10 cm i.d., 6 cm depth from funnel rim to sintered plate) with a hanging column of water below the base of the funnels (Figure 2.1).

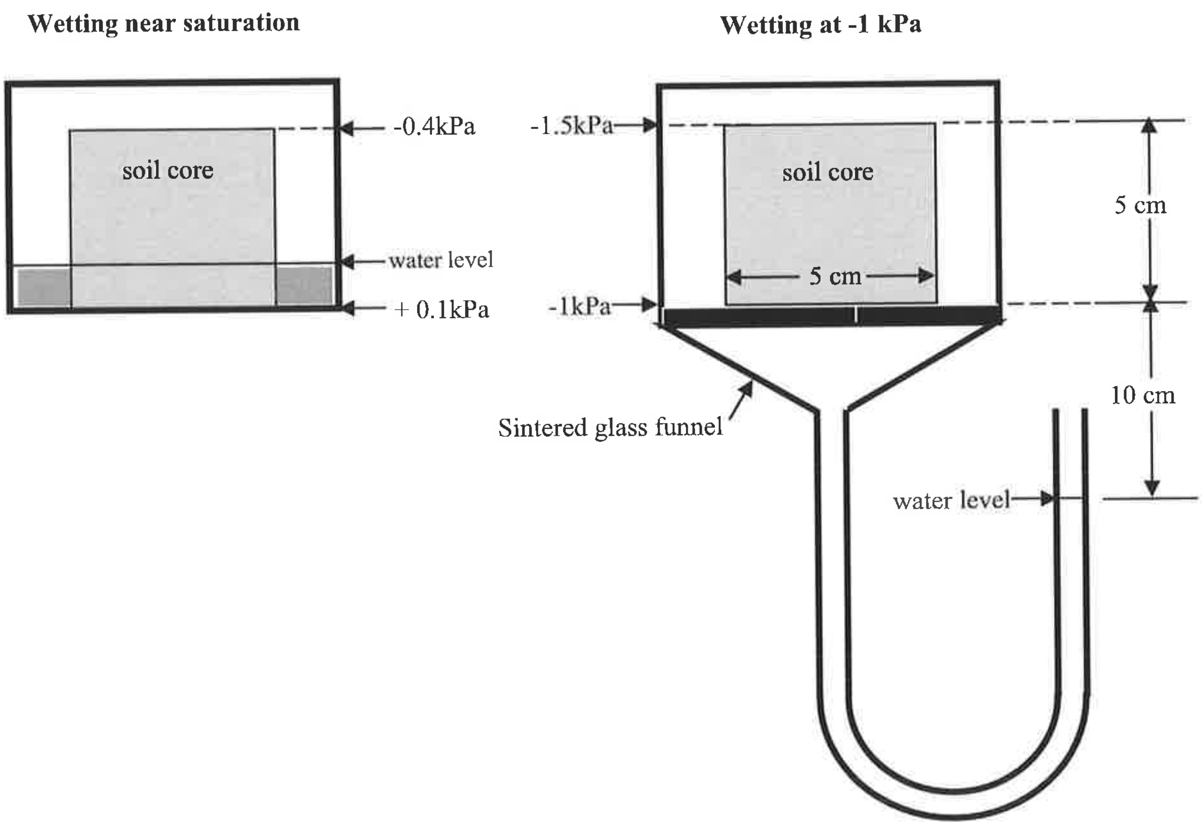

Figure 2.1. Wetting of soil cores at matric potentials near saturation and at -1 kPa (10 cm suction)

Draining

Draining at 10 kPa suction was conducted on either a sintered glass funnel or a ceramic plate (Figure 2.1) by adjusting the water column to 100 cm below the bottom of the sample. Draining at 100 kPa suction was conducted on a ceramic pressure plate in a pressure plate extractor for one week.

2.3. Soil physical measurements

Penetrometer resistance

A penetrometer is a diagnostic tool that is largely used to assess soil resistance; this is characterized as the force needed to drive a cone of specific size into the soil (Bengough *et. al.*, 2001). It is often used to estimate the resistance experienced by growing roots. In a structured soil, measured penetrometer resistance is mainly an expression of interaggregate strength (Bradford, 1986).

Many studies have shown that bulk density and water content have major influences on penetrometer resistance both in the laboratory and the field (e.g. Taylor and Gardner, 1963; Mirreh and Ketcheson, 1972; Ayers and Perumpal, 1982; Simmons and Cassel, 1989; Busscher *et. al.*, 1997). Penetrometer resistance, when measured at a standard reference water content, increases with increasing bulk density (Bennie and Burger, 1988). The relationship between penetration resistance and water content was found to be exponential as a result of water molecules reducing the cohesion between soil particles and also behaving as a lubricant between them (Vanags *et. al.*, 2004).

Soil resistance was measured by recording the force exerted by a cone penetrometer of 2 mm diameter with a recessed shaft and a total cone angle of 60^0 moving at 0.3 mm/minute as it entered the soil core resting on a digital top-loading balance. This was conducted at 5 positions in each core. At each position the load (g) was recorded at 10 second increments. Balance readings were converted to force (N) and then penetration resistance was calculated as the force divided by the area of the cone-base (Zhang *et al.*, 2001).

In all experiments, increases in penetration resistance near the bottom of the soil cores were due to the inevitably greater structural damage which occurs near the bottom of the soil cores as a result of the wetting process rather than due to proximity to the bottom of the core.

Tensile strength

Soil tensile strength was measured according to the indirect method known as the Brazilian core test (Dexter & Kroesbergen, 1985). The tensile strength, Y, (kPa) was calculated from:

$$Y = 2F/ \pi dL,$$

Where F is the load applied at the point of failure; d is the diameter of the soil core; L is the length of the soil core. Prior to tensile strength measurements, cores were air-dried slowly at room temperature (20C) until their weights were relatively constant.

Bulk density

Bulk density was obtained prior to penetrometer measurements as the ratio of the soil oven dry weight to its volume at 100 kPa suction.

Water content

The gravimetric water content was obtained by oven drying the soil at 105C for 48 h. The volumetric water content was calculated based on the volume of the soil measured at 100 kPa suction.

Turbidity

Turbidity measurements were determined using a Hach turbidimeter on soil:water (1:5) suspensions after appropriate dilution with reverse osmosis deionised (R.O.) water. For spontaneous dispersion, a 4 g sample was weighed into a 50 mL tube and 20 mL R.O. water was slowly added down the side of the tube and it was left for one hour. The tube was then gently inverted once and the suspension was left for a time appropriate for settling of 2 μm particles. The same procedure as for spontaneous dispersion was also applied for mechanical dispersion except this time the tubes were shaken more vigorously in an end-over-end shaker for 1 h with 30 revolutions per minute.

Particle size distribution

Particle size distribution was measured using dispersion, sedimentation sampling method (modified method of Day, 1965). Air-dried soil samples (<2 mm) were dispersed using 10% sodium hexametaphosphate solution, 0.6 M NaOH and R.O. water. The samples were mixed in an end-over-end shaker for up to 24 h and allowed to settle according to Stoke's Law. At an appropriate time the silt (2-20 μm) and clay (<2 μm) fractions were determined using a hydrometer, then the sand fraction was calculated by difference.

2.4. Soil chemical measurements

Organic carbon

Organic carbon content was determined on soil samples of <2 mm using the Walkley and Black rapid titration method (Nelson and Sommers, 1982).

Exchangeable cations and cation exchange capacity (CEC)

Exchangeable cations were extracted using method 15B1 of Rayment and Higginson (1992). Method 15C1 (Rayment and Higginson, 1992) was used to determine the exchangeable cations; using flame photometry for Na^+ and K^+, and atomic absorption spectrophotometry for Ca^{2+} and Mg^{2+}. The CEC was determined by displacement of NH_4^+ from soil samples leaching with K-Ca solution (15% KNO_3 and 6% $Ca(NO_3)_2.4H_20$) and the NH_4^+ was estimated by method 15I2 of Rayment and Higginson, (1992) and an auto-analyser. Exchangeable sodium percentage was calculated based on the measured CEC and the exchangeable sodium concentrations.

Electrical conductivity and pH

Electrical conductivity and pH were determined on soil:water (1:5) suspension after shaking for 1 h.

Chapter 3: Influence of matric suction on soil aggregate coalescence

3.1. Introduction

A low matric suction applied during wetting has been known to cause structural collapse during drainage of unstable soils (Mamedov *et al.*, 2001) especially those which are hardsetting due to slaking and dispersion (Gusli *et al.*, 1994a). This structural damage results in increased soil bulk density and strength. In soils with water stable aggregates, however, the effect of low matric suction on bulk density is generally less severe because slaking and dispersion are minimised. However, even soils with water stable aggregates and low bulk density which are subjected to wetting at low suction may coalesce. In particular, there is little understanding of the extent to which coalescence occurs during wetting or draining and, apart from the work of Ghezzehei and Or (2000), there is little in the published literature about coalescence of soils considered to be water stable and of good structure.

The purpose of this experiment was to investigate the effect of the magnitude of matric suction on coalescence of relatively water stable aggregates.

3.2. Materials and methods

Five soils were used; these were cultivated and virgin Shepparton fine sandy loam, cultivated and virgin Cornella clay and Wiesenboden (see Chapter 2). The aggregate size fraction 0.5–2 mm was used and packed into cylindrical rings of 5 cm and high 4.77 cm i.d. Four different wetting and draining treatments (summarised in Table 3.1) were imposed on these soil cores including: (i) wetting near saturation (see Chapter 2) with 10 kPa suction applied on draining, (ii) wetting near saturation with 100 kPa suction applied on draining, (iii) wetting at 1 kPa suction with 10 kPa suction applied on draining, and (iv) wetting at 1 kPa suction with 100 kPa suction applied on draining. These treatments were imposed so that evidence of coalescence might be identified at both field capacity (10 kPa suction) and at

100 kPa suction after preliminary wetting of the soil to near saturation (*ca.* 0.1 kPa) or to about 1 kPa suction.

Table 3.1. Summary of soil treatments

Treatment name	Matric potential applied (kPa)	
	Wetting from dry state (range from bottom to top of soil core)	Draining from wet state (*i.e.* during measurements)
0.1/10	+0.1 to –0.4	-10
0.1/100	+0.1 to –0.4	-100
1/10	-1 to –1.5	-10
1/100	-1 to –1.5	-100

Wetting at near saturation was conducted by placing soil cores into a beaker containing a free water level of 10 mm whereas wetting at 1 kPa suction was achieved by placing the soil cores on sintered glass funnels with a hanging water column of 100 mm below the base of the soil cores (see Chapter 2). These conditions resulted in matric potentials in the soil cores ranging from + 0.1 kPa to –0.4 kPa for the near-saturation (*i.e.* 0.1 kPa) treatment and from –1 kPa to –1.5 kPa for the 1 kPa treatment. The soil cores were left to reach equilibrium for 48 h after the soil surface appeared wet.

Except for the Cornella samples, drainage to 100 kPa suction was conducted on a ceramic pressure plate in a pressure plate extractor at 20C. Drainage to 10 kPa suction was carried out on a sintered glass funnel by adjusting the hanging water column to 100 cm below the base of the soil cores (Figure 2.1). All measurements were conducted on the soil cores after they had drained for either 6 d (at 100 kPa suction) and for 2 d (at 10 kPa suction). For Cornella samples, drying to 100 and 10 kPa suctions was achieved by slow air-drying until the water content, by mass, corresponded to these potentials (as determined independently from water retention curves).

The methods used for penetrometer resistance, bulk density, water content and tensile strength measurements are presented in Chapter 2.

For each soil, a completely randomised design was used with three replicates. The treatments were the suctions imposed during wetting and draining. Data was analysed using a Genstat 5 program (Genstat 5 Committee, 1987).

3.3. Results

3.3.1. Soil penetrometer resistance

Figure 3.1 shows the penetration resistance of the soils studied as a function of depth at different matric potentials applied during wetting and draining. The curves for the virgin Shepparton soil wetting at 1 kPa suction cannot be presented as the soil cores failed to fully wet even after 8 weeks, therefore this part of the experiment was aborted. The failure to wet might be attributed to the effect of air-drying of this soil with its low clay content and high organic matter content (2.8% C). According to Emerson (1959) air-drying of soil with high organic matter content increases the contact angle of water on soil particles so that the soil is not easily rewetted. In the Shepparton soils, at 100 kPa suction during drainage, the cultivated samples that were wetted at 1 kPa suction (*i.e.* 1/100) had significantly lower penetration resistance than those wetted to near saturation (*i.e.* 0.1/100). The trend was the same for samples drained at 10 kPa suction, though this was not statistically significant ($P<0.05$). As the drainage increased from 10 to 100 kPa suction the soil penetrometer resistance consistently increased as expected in both the cultivated and virgin soils. The relative increase was more pronounced in the cultivated (120%) than in the virgin soil (30%). At the same wetting (*e.g.* 0.1 kPa) and draining (*e.g.* 100 kPa) suctions, the penetrometer resistance of the virgin soil was only about one third that of the cultivated soil.

In the Cornella soil, a lower suction during wetting (0.1/10, 0.1/100) increased the soil resistance significantly. The effects appeared to be more pronounced in the cultivated than in the virgin soil, particularly at 100 kPa suction where the increase in the cultivated soil was 93% at 25 mm depth versus only 10% in the virgin soil.

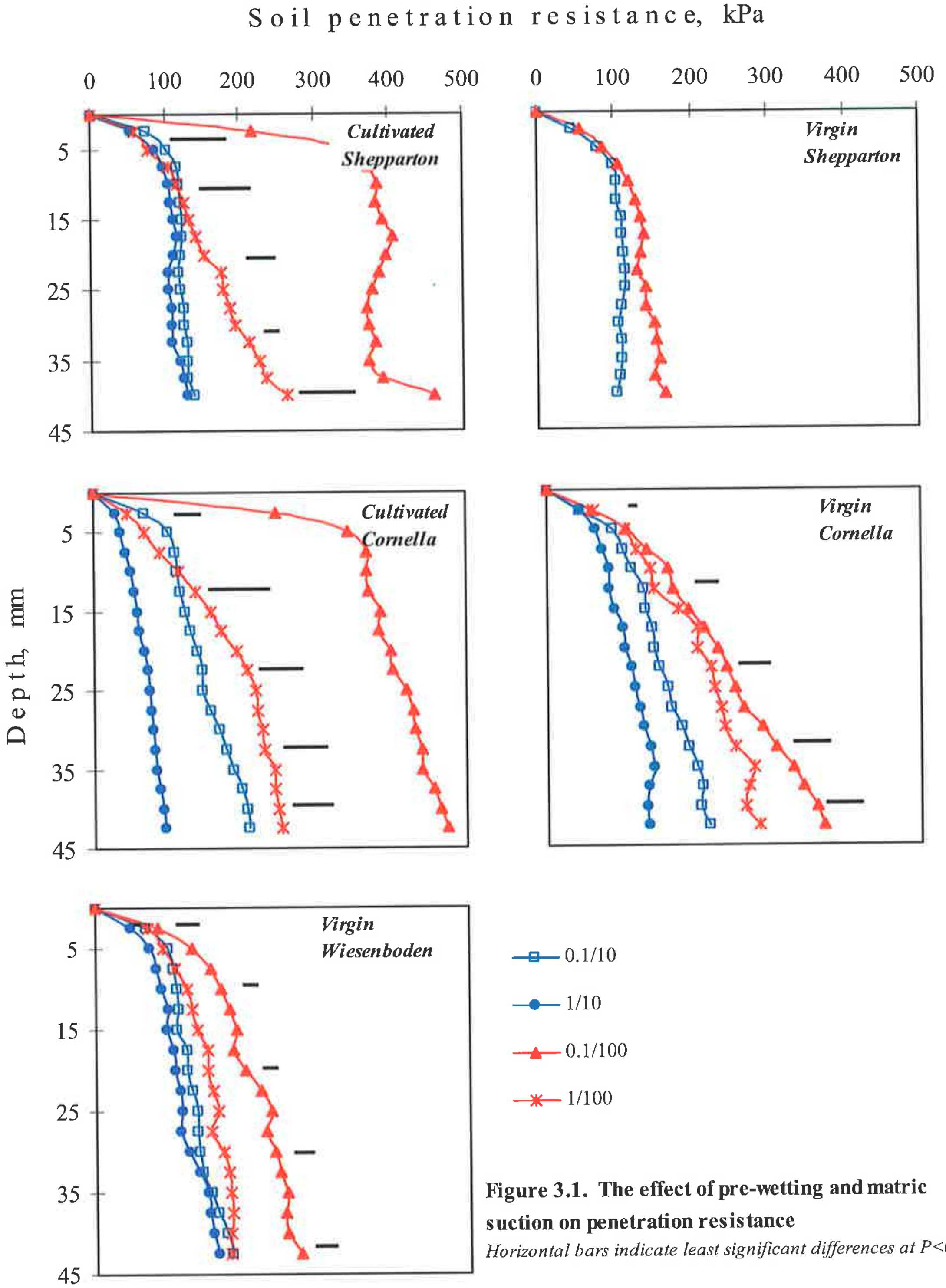

Figure 3.1. The effect of pre-wetting and matric suction on penetration resistance
Horizontal bars indicate least significant differences at P<0.05

There is no significant difference in the penetration resistance of Wiesenboden wetted near saturation and 1 kPa suction when the soils were drained at 10 kPa suction. However, when soils were drained at 100 kPa suction, the differences became significant ($P<0.05$) and as high as 45%.

3.3.2. Bulk density

Figure 3.2 shows the changes in bulk density for the soils studied. The virgin soils (Shepparton and Cornella) had lower bulk densities than their cultivated counterparts.

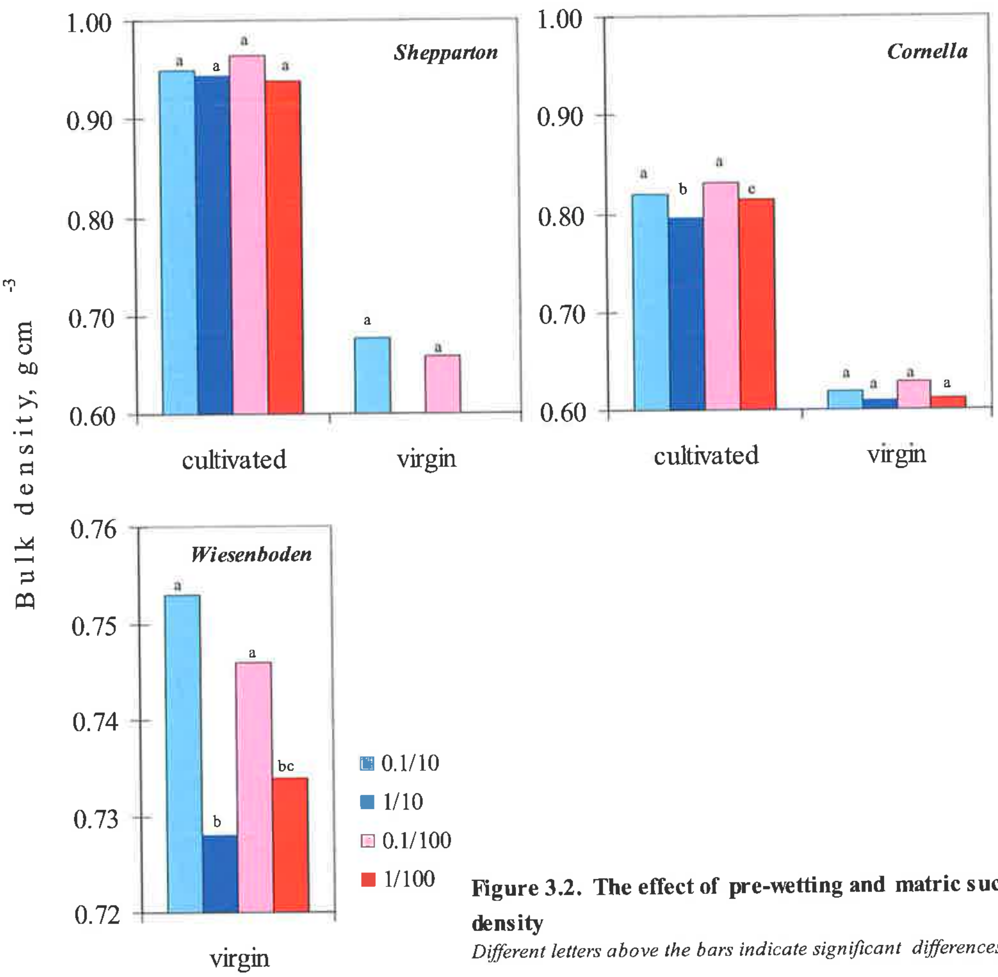

Figure 3.2. The effect of pre-wetting and matric suction on bulk density
Different letters above the bars indicate significant differences at P<0.05

The effect of wetting and draining suctions was not significant for the cultivated and virgin Shepparton soils or for the virgin Cornella soil. However, for the cultivated Cornella soil, increasing the wetting-suction from near saturation to 1 kPa decreased the bulk density significantly at both drainage suctions of 10 and 100 kPa. The bulk density of Wiesenboden showed a similar trend to the cultivated Cornella soil.

3.3.3. Water content

Table 3.2 shows the influence of different suctions applied on wetting and draining on the water content of the soils studied. Regardless of the wetting pathway, all soils showed lower water contents when drained at 100 kPa suction. The water content was found to decrease significantly as the pre-wetting increased from near saturation to 1 kPa suction for the cultivated Shepparton soil, cultivated Cornella soil and Wiesenboden when these soils were subsequently drained at 10 kPa suction.

Table 3.2. Water contents (g g^{-1}) of soils drained to 10 and 100 kPa suctions as affected by various matric suctions on wetting.

Treatment	Shepparton		Cornella		Wiesenboden
	Cultivated	Virgin	Cultivated	Virgin	Virgin
0.1/10	0.175[a]	0.233[a]	0.477[a]	0.468[a]	0.460[a]
1/10	0.155[b]	n.a.	0.429[b]	0.444[a]	0.420[b]
0.1/100	0.122[c]	0.204[b]	0.373[c]	0.346[b]	0.392[c]
1/100	0.130[c]	n.a.	0.378[c]	0.329[b]	0.385[c]
LSD	0.011	0.023	0.020	0.032	0.007

In each column, different letters indicate significant differences at $P<0.05$
n.a., not assessed

3.3.4. Tensile strength

Figure 3.3 shows that apart from the virgin Shepparton soil, which had zero tensile strength, all soils displayed significantly greater tensile strengths when wetted to near-saturation (0.1 kPa suction). The tensile strength of the cultivated Shepparton soil increased from zero, when wetted at 1 kPa suction, to 3 kPa, when wetted at 0.1 kPa suction. The cultivated soils of higher clay content generally had higher strengths. The strengths of the cultivated Cornella soil increased from only 6 to 20 kPa and for Wiesenboden from 2 to 10 kPa.

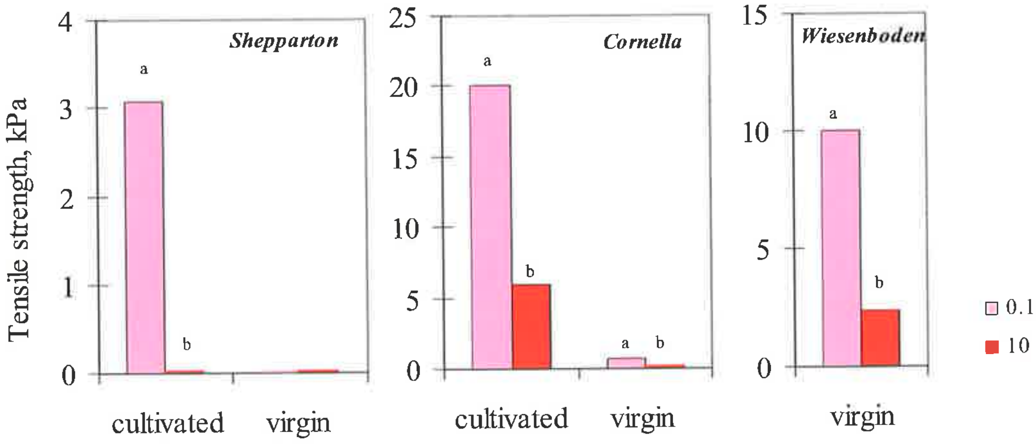

Figure 3.3. The effect of matric suction during pre-wetting on tensile strength of the air-dried soils
Different letters indicate significant differences at P<0.05

3.4. Discussion

The trends in soil penetration resistance and water content as affected by various suctions applied during wetting and draining were similar for all soils studied even though they varied in texture and mineralogy. In general, at a drainage suction of 10 kPa, all soils showed increased penetration resistance and water content when pre-wet to near saturation rather than to only 1 kPa suction. For pre-wetting to near saturation, rapid wetting caused some soil structure to collapse due to slaking and dispersion with a consequent increase in the amount of fine pores and this caused more water to be retained. Although the water contents of the 0.1/10 soils were higher than those in the 1/10 soils, the penetration resistances of the 0.1/10 soils were also higher. The higher bulk densities of the 0.1/10 soils may account for this.

At a drainage suction of 100 kPa suction, the 0.1/100 soils showed larger penetration resistance than the 1/100 soils, and this was with similar water contents for both soils. This suggests on the one hand, that water contents are a good indicator of soil structural damage only at lower suctions (10 kPa). On the other hand, however, the structural damage indicated by measured penetration resistances may only be evident at higher matric suctions (100 kPa). The insignificant differences in bulk densities between the 1/10 and 0.1/10 cultivated Shepparton soils might indicate that the structural change in the 0.1/10 soils was due to aggregate coalescence. Thus, the impact of rapid wetting on aggregate coalescence will not be apparent until the water suction is sufficiently high (e.g. 100 kPa). The role of water in contributing to soil strength when matric suction increases arises from the fact that it affects the state of effective stress within the soil. The effective stress progressively increases with increasing water suction reaching a maximum at a certain suction (Marshall and Holmes, 1988). Thus, at lower matric suctions (10 kPa), the effective stress is minimal and it becomes larger at higher matric suctions (100 kPa).

In the absence of a change in bulk density or water content at a given suction, any increase in strength may have resulted from coalescence of soil aggregates- the welding together of aggregates at contact points. Nevertheless, the increase in the water content of the cultivated Shepparton at a drainage suction of 10 kPa after pre-wetting near saturation suggests that structural damage of the kind associated with incipient failure (Quirk & Panabokke, 1962) might occur in this soil. This damage seems not to be obvious in the bulk density measurements as they were very similar for both pre-wetting suctions; however, the results from penetrometer resistance appeared to confirm the damage.

Generally, both the virgin Shepparton and Cornella soils had lower penetration resistances and bulk densities than their cultivated counterparts. The organic matter contents in the virgin soils were much higher than in the cultivated soils. The carbon contents were found to be 2.8% in the virgin Shepparton soil and 3.7% in the virgin Cornella, whereas in the cultivated Shepparton and Cornella soils they were only 1.5 and 1.2%, respectively. Apart from the lower bulk densities, organic matter may protect soil structure from damage in various ways. Apart from its effect on aggregate stability, organic matter in particulate forms may either slow water uptake rates due to its hydrophobic behavior (*e.g.* Franco *et al.*, 2000), or else act as physical barriers between aggregates preventing them from coalescing (Grant *et al.*, 2001). According to Quirk and Panabokke (1962), organic matter strengthens coarse soil pores against failure. These coarse pores usually experience more rapid wetting than the fine ones. Therefore, organic matter facilitates water management in that soils can be worked over a wider range of water potentials with a relatively lower risk of structural damage.

The penetrometer resistance of the virgin Shepparton soil was generally lower than that of the virgin Cornella soil, although the organic matter content was higher in the latter. This seems to indicate that the influence of organic matter on soil strength may be more effective in the coarser-textured than in finer-textured soils where the clay content is 3-4 times higher. In this regard it is worth noting that Smith *et al.* (1997) included organic matter content as an independent variable in their penetration resistance model for soils with less than 30% clay but excluded it from the model when the clay content was more than 30%. They argued that the levels of organic carbon contents in the high clay content soils (1-15%) were not sufficiently high to have a large effect on penetration resistance.

The significant increase in tensile strength resulted from decreased matric suction on pre-wetting for all soils (except virgin Shepparton), and this confirmed the soil structural decline suggested by the penetration resistances.

3.5. Conclusions

Regardless of soil texture and mineralogy, fast wetting (near saturation) seems to cause aggregate coalescence. The effects of rapid wetting on aggregate coalescence are manifest in higher water contents when the soil is drained to near field capacity (10 kPa suction), greater penetration resistance as the soils drains further (100 kPa suction), and greater tensile strength when the soil is air dried. Organic matter moderates the effect of fast wetting on aggregate coalescence by stabilising the aggregate, reducing wetting rate, or acting as physical barriers between aggregates.

Chapter 4: Influence of repeated wetting/draining on aggregate coalescence

4.1. Introduction

Wetting and draining cycles may increase soil strength either due to age hardening processes (Utomo and Dexter, 1981) or to bulk density increase (Gusli *et al.*, 1994a) or a combination of both. These processes may occur in both water stable and unstable aggregates. In unstable aggregates, an increase in bulk density is always accompanied by soil strength increase, while in soils with relatively water stable aggregates increased soil strength may not necessarily be accompanied by a large increase in bulk density (aggregate coalescence). Grant *et al.* (2001) attempted to make a distinction between an increase in soil strength simply due to bulk density accompanied by the age hardening process, or that merely due to the age hardening process alone, by introducing a measure, χ, that could possibly be used to separate these phenomena:

$$\chi = \Delta Y / \Delta \rho_b,$$

where Y can be either tensile strength or penetrometer resistance, and ρ_b is the soil bulk density. It was found that a constant χ over time could indicate either increasing soil strength as a result of densification without necessarily involving age hardening, or no change at all. On the contrary, increasing χ with time can be due to age hardening. However, as χ is an index that has no indicative value, its values only show trends.

The experiment described here aimed to determine the effect of wetting and draining cycles on aggregate coalescence of relatively water stable aggregates, as measured by χ and its components.

4.2. Materials and methods

Aggregates of 0.5 – 2 mm from five soils were used: cultivated and virgin Shepparton, cultivated and virgin Cornella and virgin Wiesenboden (Chapter 2). These aggregates were packed into stainless steel rings (5 cm high, 4.77 cm i.d.). The soil cores were subjected to 1, 2, 5 and 8 cycles of wetting to near saturation followed by draining at 100 kPa suction (Chapter 2). Each cycle consisted of 1 period of wetting (24 h) and 1 period of draining (6 d on pressure plates). After each cycle, the cores were re-wetted to near saturation and returned to the pressure plates until the required number of cycles had occurred.

Measurements of bulk density, soil penetration resistance, and gravimetric water content were conducted on samples directly after they were taken off the 100 kPa pressure plates. Tensile strength of air-dried soil cores was measured.

For each soil, a completely randomised design was used with three replicates. The treatments were the number of cycles. Data was analysed using a Genstat 5 program (Genstat 5 Committee, 1987).

4.3. Results

4.3.1. Penetrometer resistance

Figure 4.2 shows the penetration resistance of the soils studied as a function of soil depth and as affected by the number of wetting/draining cycles. Penetration resistance invariably increased with depth in the soil, regardless of organic matter status (i.e. virgin or cultivated). Trends in soil resistance were more pronounced in the cultivated than in the virgin soils. In the Shepparton soil, repeated wetting (near saturation) and draining (100 kPa suction) gradually increased soil resistance. The increase was significant for the cultivated soil but not for the virgin soil.

Wetting and draining cycles had no significant effect on soil resistance of the cultivated and virgin Cornella soils nor on the Wiesenboden. The soil resistance increased to a maximum after the 5th cycle of wetting/draining, and then decreased with subsequent wetting and draining.

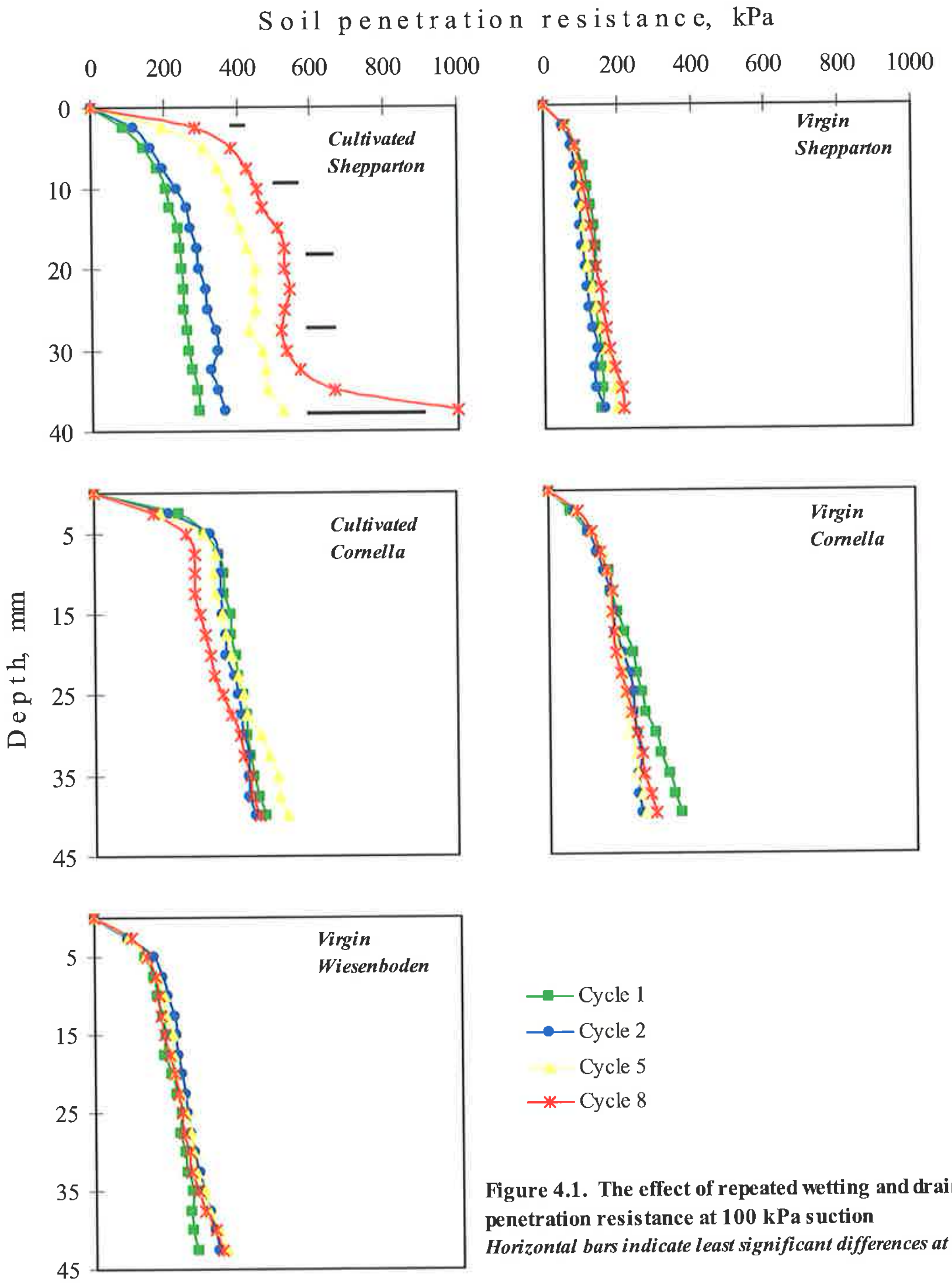

Figure 4.1. The effect of repeated wetting and draining on penetration resistance at 100 kPa suction
Horizontal bars indicate least significant differences at P<0.05

4.3.2. Bulk Density

Figure 4.2 shows the bulk densities of the soils studied as affected by repeated wetting and draining. The first bars (at the left-hand side of each graph) indicate the initial bulk density when the air-dried aggregates were packed, and when wetting had not yet commenced. The bulk densities of the cultivated Shepparton soil at the 1st and 2nd cycles of wetting and draining were similar to the initial bulk density and then increased significantly after the 5th cycle, while in the virgin soil, the increase was significant after just the 2nd cycle. The bulk densities of the cultivated soil were generally low (<1.06 g cm^{-3}), but were always greater than those of the virgin soil (~0.66 g cm^{-3}).

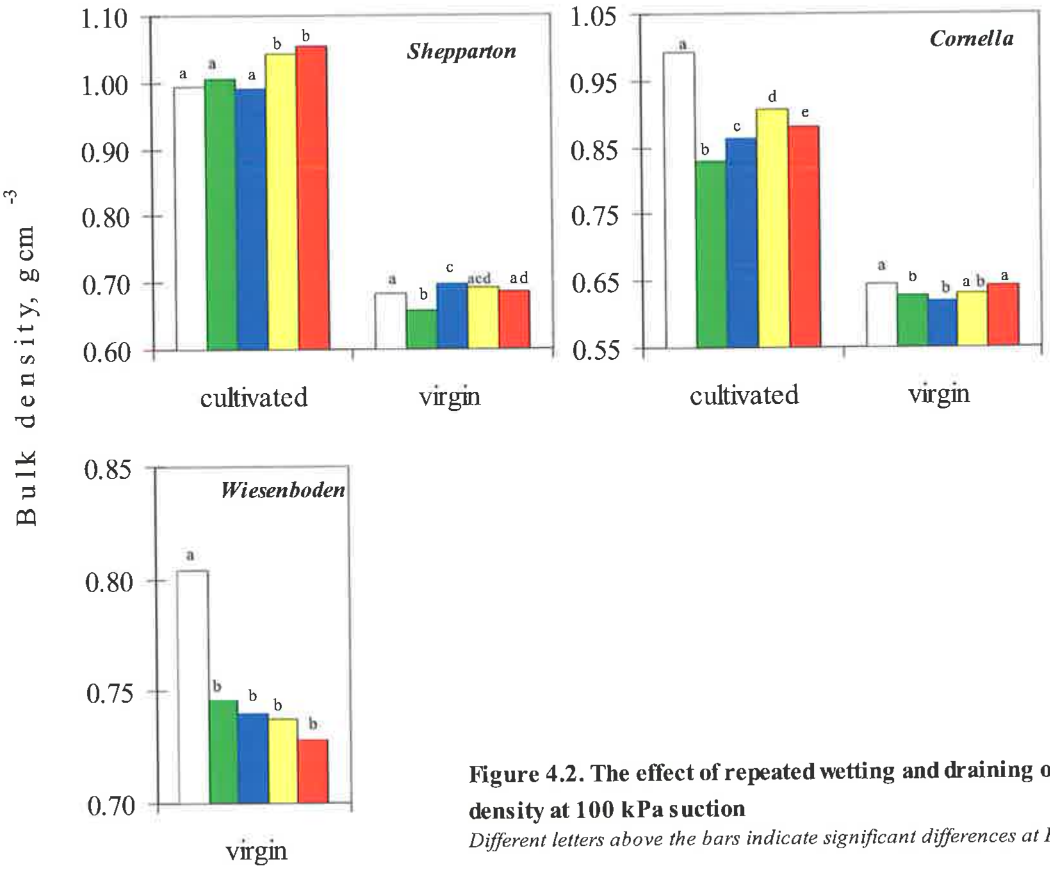

Figure 4.2. The effect of repeated wetting and draining on bulk density at 100 kPa suction
Different letters above the bars indicate significant differences at P<0.05

For the Cornella soil, the bulk density of the cultivated soil increased (from 0.83 to 0.90 g cm^{-3}) with repeated wetting and draining cycles until the 5th cycle, after which it declined modestly to 0.88 g cm^{-3} by the 8th cycle. The bulk density of the virgin soil was at least 30% lower than that of the cultivated soil (only ~0.64 g cm^{-3}), and changed significantly only by the 8th cycle.

Wiesenboden showed a gradual reduction in the bulk density with repeated wetting and draining, although the changes were not significant.

4.3.3. Water content

Table 3.1 shows the water content of the soils studied as affected by repeated wetting and draining. The cultivated Shepparton soil generally had lower water content (~0.12 g g^{-1}) than the virgin soil (~0.2 g g^{-1}), and these increased slightly with repeated wetting and draining up to the 5th cycle, then decreased. The increases were significant for the cultivated soil but not for the virgin soil.

The water content of the cultivated and virgin Cornella soils increased steadily from 0.35 to 0.37 g g^{-1} throughout all wetting and draining cycles but the changes were not significant. A trend similar to that of the Cornella soil was also found for Wiesenboden.

Table 4.1. Soil Water contents (g g^{-1}) at 100 kPa suction as affected by wetting and draining cycles

Treatment	Shepparton		Cornella		Wiesenboden
	Cultivated	Virgin	Cultivated	Virgin	Virgin
Cycle 1	0.109^{a}	0.224^{a}	0.351^{a}	0.346^{a}	0.392^{a}
Cycle 2	0.122^{b}	0.231^{a}	0.360^{a}	0.359^{a}	0.386^{a}
Cycle 5	0.126^{b}	0.246^{a}	0.366^{a}	0.381^{a}	0.412^{a}
Cycle 8	0.110^{a}	0.230^{a}	0.369^{a}	0.375^{a}	0.404^{a}
LSD	0.012	na.	na	na	na

In each column, different letters indicate significant differences at $P<0.05$
na., not applicable

4.3.4. Tensile strength

Figure 4.3 shows the tensile strength of the soils studied as affected by repeated wetting and draining. The tensile strength of the cultivated Shepparton soil progressively increased with time whereas the virgin soil had effectively zero strength.

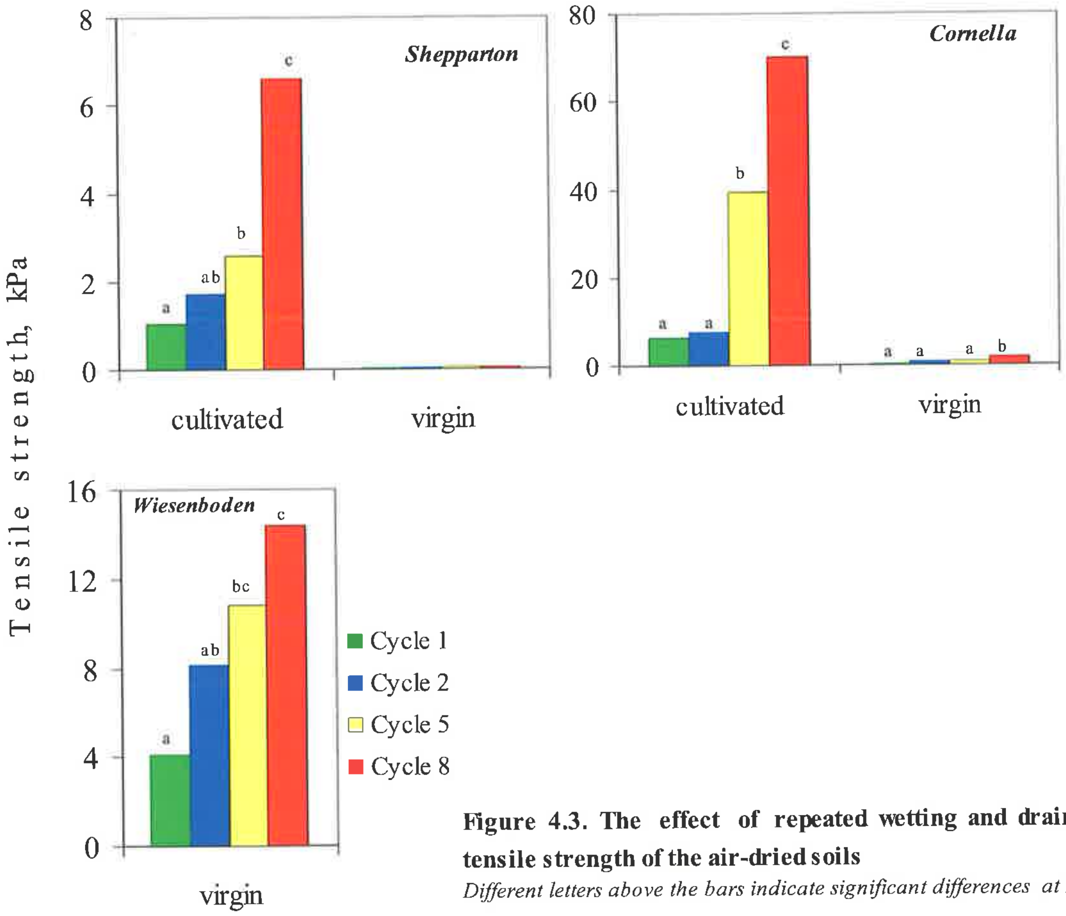

Figure 4.3. The effect of repeated wetting and draining on tensile strength of the air-dried soils
Different letters above the bars indicate significant differences at $P<0.05$

The tensile strengths of the cultivated and virgin Cornella soils were found to show a similar trend, again with the values for the virgin soil much smaller than its cultivated counterpart. The tensile strength of the cultivated soil was similar between the 1st and 2nd cycles, but then increased sharply by the 5th cycle and again by the 8th cycle, while in the case of the virgin soil, no increase was seen until the 8th cycle. In the Wiesenboden, the tensile strength increased significantly with repeated wetting and draining.

4.4. Discussion

The strongest trends in soil resistance were seen in the cultivated Shepparton soil. Repeated wetting and draining in soil might weaken the soil aggregates by various processes working in concert during wetting causing the soil to slake. The processes known to be responsible for slaking include differential swelling (Emerson, 1977), air entrapment (Panabokke and Quirk,

1957) and the heat of wetting (Collis-George and Greene, 1979). This condition might lead to the creation of more contact points as the aggregates become smaller and their packing arrangement denser; increasing bulk density partly confirms this (Figure 4.3). The increase in water content by the 2^{nd} and 5^{th} cycles and then a decrease may indicate that at first a collapse of the aggregates created more fine pores at the expense of large ones but that pore collapse may have continued so that water content decreased again. The significantly higher water content by the 2^{nd} and 5^{th} cycles could also indicate that the soil penetration resistances at these points might be somewhat higher if they had been measured at water contents similar to those in cycles 1 and 8. Although the increase in the bulk density appeared to be minimal, its impact on frictional resistance between the penetrometer and the soil may be significant as indicated by Bengough and Mullins (1990). Another explanation for this increased resistance may be found in the strength of the bonds between aggregates which may increase due to age hardening as shown by increasing tensile strength values (Figure 4.2) although the values appeared to be small.

The virgin Cornella soil resistances declined slightly after the 1^{st} cycle, although the changes were not significant, whereas this took up to five wetting and draining cycles to occur in the cultivated soil. It would appear that the high organic matter might have played an important role in this process. Nevertheless, the self-mulching nature of the Cornella soil may have contributed to the decline after the 5^{th} cycle. Although the cultivated Cornella clay shows no particular trend in soil penetrometer resistance as affected by repeated wetting and draining, tensile strength may show how aggregate coalescence develops in this soil. The tensile strength progressively increased with repeated wetting and draining, particularly after the 2^{nd} cycle, indicating that aggregate coalescence actually develops as time progresses. The same trend is also found in Wiesenboden. According to Utomo and Dexter (1981) bonds between aggregates may become stronger due to the age hardening process as time progress. As tensile strength actually measures the cohesive force between aggregates, its measurement may be more relevant in identifying the development of aggregate coalescence than the penetrometer resistance measurement.

A significant increase in tensile strength by the 8th cycle observed for the virgin Cornella indicates that aggregate coalescence also develops in this soil but at a slower rate due to its high organic matter content. Organic matter may act in two ways to retard strength development. In particulate form, it may act as a physical barrier between aggregates and, in this and other forms, it may improve the stability of individual aggregates to slaking and dispersion.

4.4.1. Coalescence measurements

This section attempts to quantify soil aggregate coalescence following Grant *et al.* (2001). The ratio, χ_1, was used as a measure of coalescence as discussed in 4.1. which is:

$$\chi_1 = \Delta Q_p / \Delta \rho_b,$$

where Q_p is soil penetration resistance and ρ_b is soil bulk density. The penetrometer resistance values used were those taken at a depth of 25 mm. Figure 4.4 shows the values of χ_1 with repeated wetting and draining. The average χ values vary considerably from large and negative (-28 MPa/g cm^{-3}) in the virgin Cornella soil to large and positive (7 MPa/g cm^{-3}) in the cultivated Shepparton soil. These negative values arise from the fact that either the soil penetration resistance decreased with time or the bulk density decreased with time.

The effect of wetting and draining cycle on χ_1 was not significant for all soils studied. Almost every soil shows that the average χ_1 appeared to be relatively constant with repeated wetting and draining, suggesting that any increases in soil strength (penetration resistance) were merely due to bulk density.

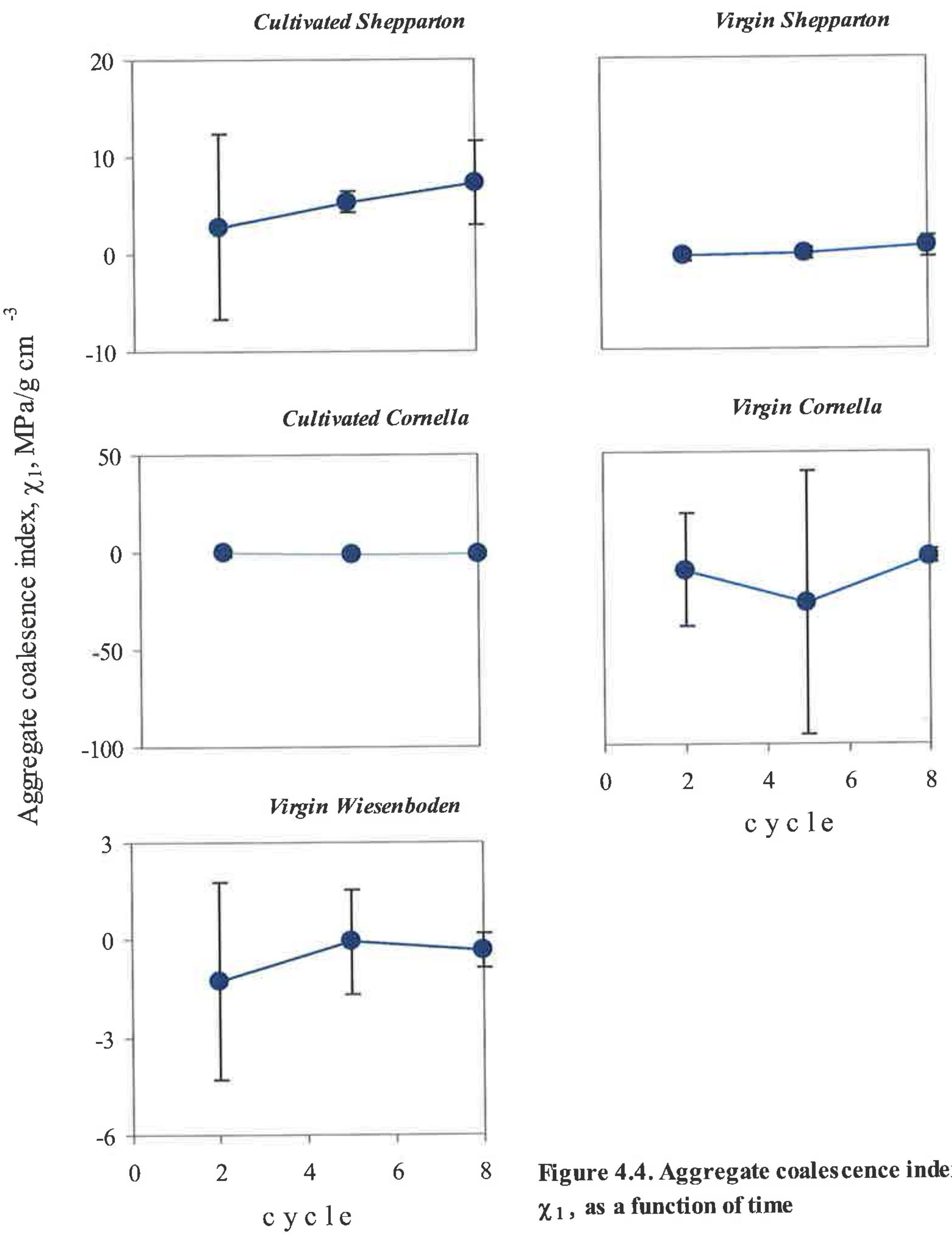

Figure 4.4. Aggregate coalescence index, χ_1, as a function of time

Based on tensile strenght, aggregate coalescence was quantified using the following equation:

$$\chi_2 = \Delta S_p / \Delta \rho_b,$$

Where S is soil tensile strength and ρ_b is soil bulk density. In this measurement, soil bulk density were taken from the soil cores used for the penetrometer resistance measurements as there were no bulk density measurements for the soil cores used for tensile strength measurements. This was due to the measurements of tensile strength were conducted on air-dried soil cores where the cores sometimes needed to be reshaped because some aggregates were detached from the cores, so only the core diameter and high were taken for the calculation of the tensile strengths. Therefore, χ_2 was calculated based on an average value of tensile strengths to an average value of bulk densities taken from the soil cores of penetrometer measurements. Figure 4.5 shows the value of χ_2 with repeated wetting and draining cycles. As the virgin Shepparton and Cornella soils had zero tensile strength for almost any cycle Figure 4.5 only presents their cultivated counterpart soils and Wiesenboden.

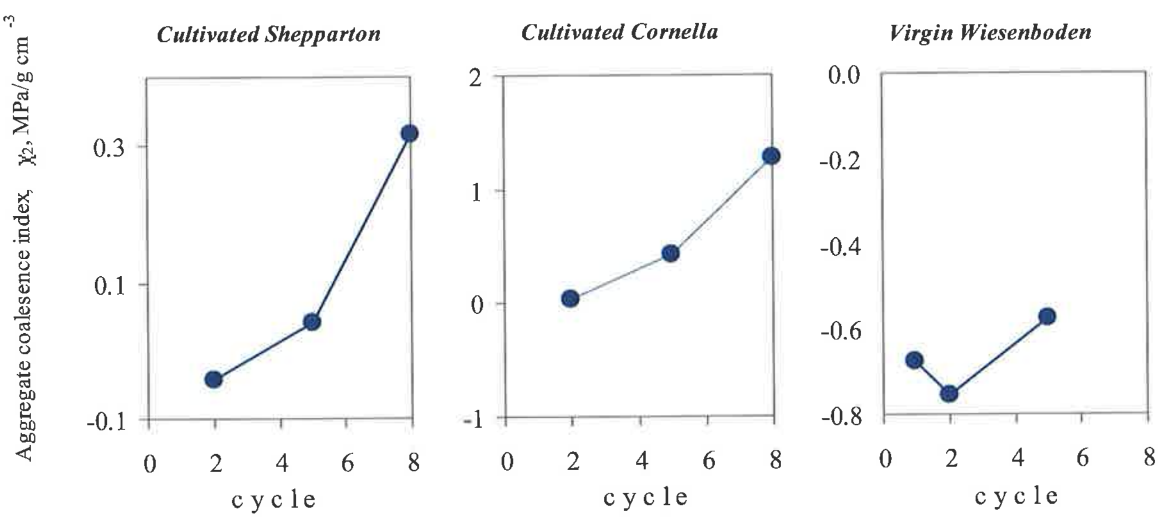

Figure 4.5. Aggregate coalescence index, χ_2, as a function of time

All soils show similar trend in which the χ_2 increase with repeated wetting and draining cycles. This suggests that aggregate coalescence actually develop as time progresses in which the bond between aggregates might have become stronger with time possibly due to age hardening.

4.5. Conclusions

In the non-swelling soil, Shepparton, repeated wetting and draining gradually increased soil penetrometer resistance and bulk density, but water content increased by the 2^{nd} and 5^{th} cycles and decreased by the 8^{th} cycle. For the two swelling soils (Cornella and Wiesenboden), both exhibited insignificant changes in soil resistance, bulk density and water content with wetting/draining, though after several cycles of wetting/draining, there appeared to be some reduction in soil resistance and bulk density and an increase in water content. Organic matter in soil from the virgin sites tended to reduce the magnitude of the effects on bulk density, soil resistance and water content with repeated wetting and draining. The virgin soil always had lower bulk densities and soil resistances, and higher water contents.

The different water content at 100 kPa suction in a given soil tend to undermine the use of penetrometer resistance as a means of detecting aggregate coalescence, and suggests that it might be less reliable than the tensile strength of the air-dried soil. The relatively constant values of χ which were based on changes in penetrometer resistance and bulk density also suggested that there were no significant development of aggregate coalescence with repeated wetting and draining cycles in the soils studied in these experiments. The increases in χ values based on changes in tensile strength and bulk density may indicate that tensile strength is more reliable in detecting the development of aggregate coalescence with wetting and draining cycles.

Chapter 5: Influence of overburden on soil aggregate coalescence

5.1. Introduction

An open soil structure inevitably consolidates after tillage due to overburden pressure (Koolen and Kuipers, 1989) and its bulk density increases once irrigation commences (Ghavami *et al.*, 1974). Even in un-tilled soils, bulk densities consistently increase with depth (Cannel, 1985). Field observations have indicated that aggregate coalescence is first expressed at the bottom of the seedbed and develops progressively upward to the soil surface during the growing season (e.g. B. Cockroft and C.D. Grant pers. Comm.) This suggests that overburden pressures may enhance aggregate coalescence by increasing the degree of inter-aggregate contact.

The purpose of this experiment was to determine the effects of overburden on coalescence of water stable soil aggregates.

5.2. Materials and methods

Five soils including cultivated and virgin Shepparton soils, cultivated and virgin Cornella soils and virgin Wiesenboden were used in this experiment. Aggregate fractions of 0.5-2 mm were packed into cylindrical rings (5 cm high and 4.77 cm i.d.) with thin mesh at the base. Perforated brass cylinders of 4.5 cm diameter and of 4 various weights (0, 80, 240, and 400 g) were set on top of the soil cores. Based on assumptions of a dry bulk density of 1.2 g cm^{-3} and of a volumetric water content of 0.3 cm cm^{-3}, these weights simulated reasonable static load pressures of 0, 0.49, 1.47 and 2.47 kPa in the root zone which are equivalent to depths of 0, 3.4, 10.1 and 16.8 cm. The soil cores were subjected to wetting near saturation for 24 hours and then drained at 100 kPa suction (Chapter 2). In the following text, the overburden pressures will be referred as 0, 0.5, 1.5 and 2.5 kPa

The methods used for measuring penetrometer resistance, bulk density, water content and tensile strength are presented in Chapter 2.

For each soil, a completely randomised design was used with three replicates. The treatments were overburdens. Data was analysed using a Genstat 5 program (Genstat 5 Committee, 1987).

5.3. Results

5.3.1. Penetrometer resistance

Figure 5.1 shows penetrometer resistance of the soils studied as a function of soil depth with various overburden pressures.

As might be expected, the penetration resistance of the Shepparton soil increased in approximate proportion to the applied overburden, particularly for the cultivated soil. At 25 mm depth, the resistance increased from 253 to 586 kPa when the overburden pressure increased from zero to 2.5 kPa. For the virgin sample, soil resistance also increased with applied overburden, but much less so than in the cultivated soil. For example, the profile of soil resistance for the un-burdened cultivated soil was similar to that of the virgin soil with the largest overburden pressure (2.5 kPa).

For the Cornella soil, the effects of overburden were enhanced with depth, particularly in the cultivated soil, where the soil resistance (under 2.5 kPa pressure) tripled from ~300 kPa at the top of the core to over 1000 kPa at the bottom. By contrast, the virgin soil showed very little change with depth in the soil core, such that under an overburden pressure of 2.5 kPa the soil resistance ranged from ~200 kPa at the top of the core to only ~400 kPa at the bottom. That is, the profiles of penetration resistance in the virgin soil were generally more uniform than in the cultivated soil.

The penetration resistance of Wiesenboden consistently increased with soil depth as well as overburden. Soil resistance increased in approximate proportion to the overburden applied. At 25 mm, the penetration resistance increased from 238 to 417 kPa when the overburden pressure increased from zero to 2.5 kPa.

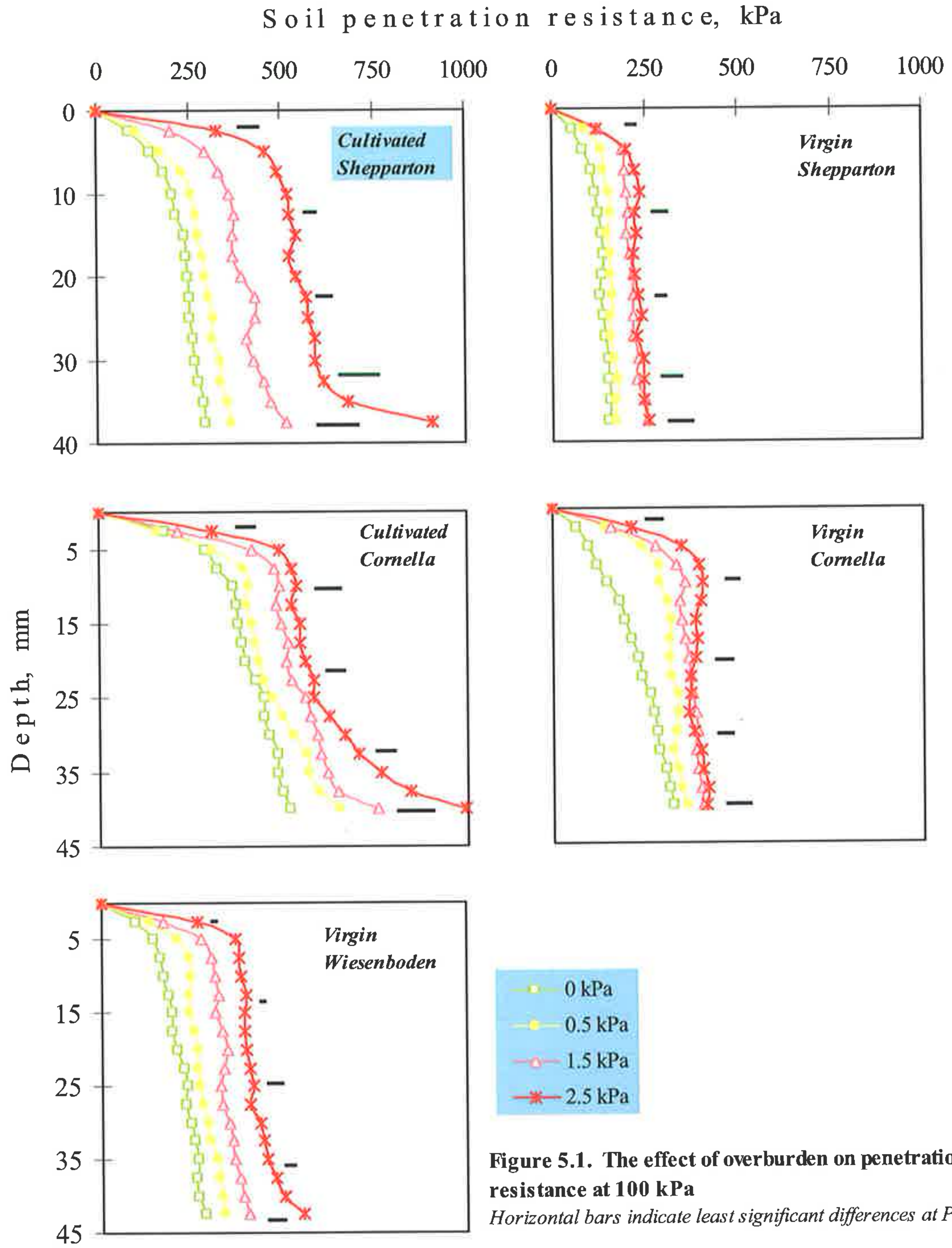

Figure 5.1. The effect of overburden on penetration resistance at 100 kPa
Horizontal bars indicate least significant differences at P<0.05

5.3.2. Bulk density

Figure 5.2 shows the bulk density of the soils studied. Increasing overburden pressures significantly ($P<0.05$) affected the bulk density of the cultivated Shepparton soil although the increase appeared to be small. It increased from ~1.01 g cm^{-3} up to ~1.14 g cm^{-3}. The effect of overburden on the bulk density of the virgin soil was not statistically significant at $P<0.05$ (from ~0.67 g cm^{-3} up to ~0.69 g cm^{-3}).

The effect of overburden on the bulk density of the Cornella soils was statistically significant at $P<0.05$. Bulk densities generally increased with increasing overburden and the rates of the increase were approximately the same for both virgin and cultivated soils (~0.89 up to 0.94 g cm^{-3} for cultivated, and ~0.61 up to 0.65 g cm^{-3} for virgin) as the overburden pressures increased from 0 to 2.5 kPa.

The bulk densities of Wiesenboden increased significantly with increasing overburden (from 0.73 g cm^{-3} to 0.79 g cm^{-3}).

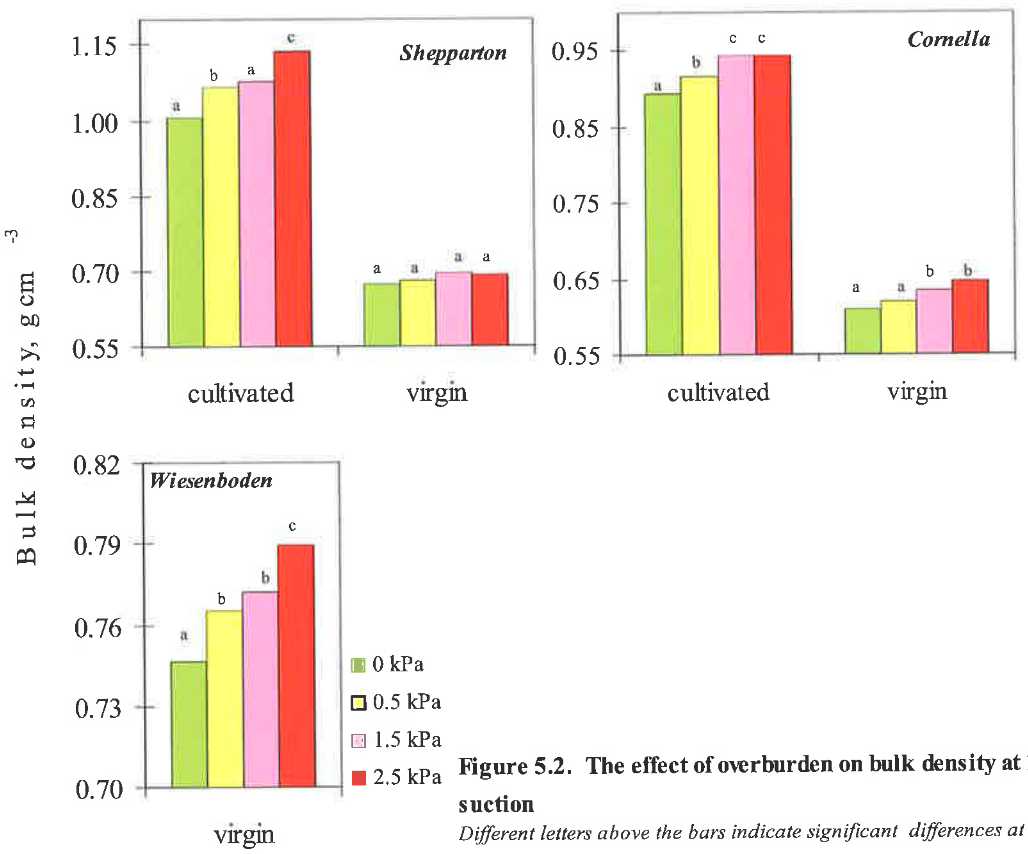

Figure 5.2. The effect of overburden on bulk density at 100 kPa suction
Different letters above the bars indicate significant differences at P<0.05

5.3.3. Water content

Table 5.1 shows water contents for the various overburden pressures. The effect of overburden on the water contents of the two Shepparton soils (cultivated and virgin), the virgin Cornella and the Wiesenboden was not statistically significant. The water contents increased significantly with increasing overburden only in the cultivated Cornella soil.

Table 5.1. Soil Water contents (g g^{-1}) at 100 kPa suction as affected by overburden

Overburden (kPa)	Shepparton		Cornella		Wiesenboden
	Cultivated	Virgin	Cultivated	Virgin	Virgin
0	0.109^a	0.205^a	0.311^a	0.298^a	0.392^a
0.5	0.112^a	0.209^a	0.331^b	0.317^a	0.396^a
1.5	0.106^a	0.196^a	0.330^b	0.325^a	0.399^a
2.5	0.107^a	0.204^a	0.337^b	0.328^a	0.381^a
LSD	na	na	0.013	na	na

In each column, different letters indicate significant differences at $P<0.05$
na, not applicable

5.3.4. Tensile strength

Figure 5.3 presents the tensile strength as affected by overburden. Overburden did not affect the tensile strength of the virgin Shepparton which had zero tensile strength at all levels of overburden. The effect, however, was found to be significant in the cultivated soil. The tensile strength was relatively constant at overburden pressures less than 1.5 kPa but then increased considerably at 2.5 kPa.

Overburden significantly affected the tensile strength of both the cultivated and virgin Cornella soils, although the absolute magnitude of tensile strength was smaller for the virgin soil than for its cultivated counterpart. In the cultivated soil, the tensile strength increased markedly from 19 to 46 kPa as the overburden pressure increased from 0 to 2.5 kPa while in the virgin soil, the increase was from 0.2 to 2 kPa.

The tensile strength of Wiesenboden was also significantly affected by the overburden. The tensile strength consistently increased with overburden in which the largest increase occurred when the overburden increased from 1.5 to 2.5 kPa.

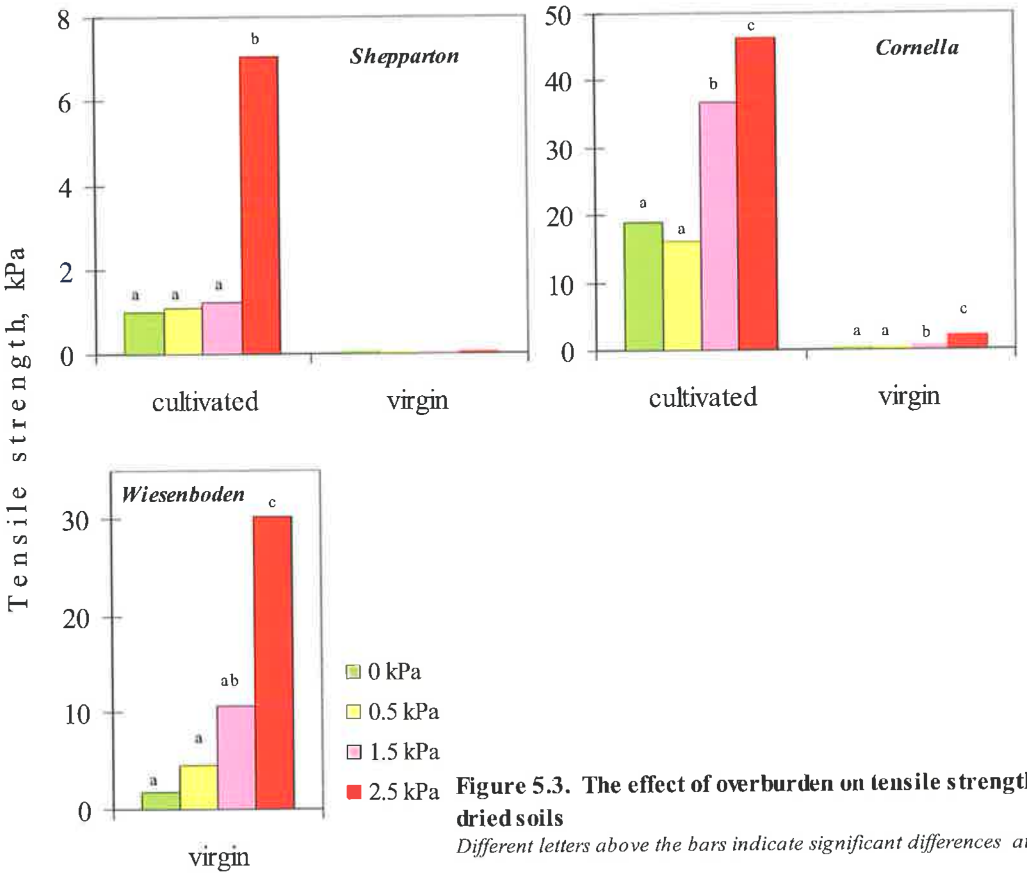

Figure 5.3. The effect of overburden on tensile strength of the air-dried soils
Different letters above the bars indicate significant differences at $P<0.05$

5.4. Discussion

All soils showed significant increases in penetration resistance and bulk density as a result of increasing overburden pressures, while for the water content, only the cultivated Cornella clay showed a significant increase. The effects of overburden on penetration resistance appeared to be much greater than on bulk density. Penetration resistance increased in the range 19 - 125% for the Shepparton cultivated soil, 11 - 39% for the cultivated Cornella soil and 19 - 75% for the Wiesenboden with increasing overburden. Bulk density by contrast increased by only 6 - 13%, 2 - 5%, and 2 - 5%, respectively. Greacen (1981) found that a red brown earth (similar to Shepparton soil) had increases in bulk density of 31 - 55% which corresponded to increases in penetration resistance of 300 - 350%.

The rate of increase in soil resistance with depth was greater for the cultivated than for the virgin soils suggesting that organic matter has some protective role. For example, the effect of a 0.5 kPa overburden pressure on the penetration resistance profile for virgin Shepparton soil was relatively small, possibly suggesting that there may be a critical overburden pressure below which no effects on penetration resistance (soil structure) may occur in this soil.

In the (swelling) cultivated Cornella the increase in the bulk density was associated with an increase in water content. It seems that more fine pores were created by increased overburden so that the degree of saturation in this soil increased.

The relative increases in the tensile strength appeared to be different for each soil. The increase in tensile strength of the cultivated Shepparton soil was significant only for the largest overburden pressure (2.5 kPa), suggesting that the low clay content of this soil lead to reduced aggregate coalescence until substantial pressures were reached. Furthermore, when this soil had higher organic matter content (virgin Shepparton), aggregate coalescence appeared to be completely preventable as zero tensile strength was evident at all overburden pressures. In the fine-textured soil (Cornella), even the virgin soil showed development of aggregate coalescence with increasing overburden, although the values were smaller than that of its cultivated counterpart.

5.5. Conclusions

Soil bulk density and soil resistance increased with increasing overburden for most of the soils examined in this work. The virgin soils exhibited greater resistance to structural changes under overburden than did the cultivated soils regardless of whether the soil was swelling or non-swelling. Where densification occurred under increasing loads, the degree of saturation increased, but when densification was resisted (in virgin soils), very little change in water content occurred. Organic matter provided considerable resilience under applied overburdens. The implications appeared from this work for soil management in the field is that maintaining relatively high organic matter content in soil into larger depths could reduce the risk of aggregate coalescence development due to overburden pressure.

Chapter 6: Influence of aggregate size on soil aggregate coalescence

6.1. Introduction

Aggregate size is a factor that would seem to affect the development of soil aggregate coalescence. Aggregate coalescence is expected to be influenced by soil strength and by the way soil aggregates behave at their points of contact. The higher the number of contact points per unit volume, the greater the soil strength (Barzegar *et al.*, 1995). Other things being equal, the distribution of aggregate sizes within the soil determines the number of contact points between aggregates (Bresson and Cadot, 1992). Bresson and Moran (1995) found that a repacked seedbed of fine aggregates produced higher strength than that of coarse aggregates, a finding similar to that of Chartres *et al.* (1990). According to Barzegar (1995) the strength of soil is also controlled by the nature of the bonding at the contact points between aggregates as well as by the number of such contacts.

This experiment was conducted to investigate the effect of aggregate size on the coalescence of relatively water-stable aggregates.

6.2. Materials and methods

Three soils including cultivated and virgin Shepparton, cultivated and virgin Cornella, and Wiesenboden were used in this experiment (Chapter 2). Aggregate fractions used were of <0.5, 0.5-2, 2-4 and <4 mm. The aggregates were packed into rings 5 cm high and 4.77 cm i.d. with thin mesh at the base and subjected to wetting near saturation and draining at 100 kPa suction (Chapter 2). Measurements of penetrometer resistance, bulk density, water content and tensile strength were then conducted as described in Chapter 2.

For each soil, a completely randomised design was used with three replicates. The treatments were aggregate size. Data was analysed using a

Genstat 5 program (Genstat 5 Committee, 1987). If there was a significant effect at $P<0.05$, the analysis was continued with Least Significant Difference (LSD).

6.3. Results

6.3.1. Penetrometer resistance

Figure 6.1 shows the penetration resistance of a function of depth and as affected by aggregate size. Both cultivated and virgin Shepparton soils show similar trends in resistance for the various aggregate sizes. The values for the virgin soil aggregate fractions were significantly smaller than their cultivated counterparts. In each soil the resistance of aggregate sizes <0.5 and <4 mm appear to be similar in magnitude. The same can be said for the two aggregate sizes 0.5-2 and 2-4 mm. The two fractions containing significant quantities of <0.5 mm aggregates (*i.e.* <0.5 and <4 mm) exhibited the greatest penetrometer resistance.

The soil resistance appeared to be relatively constant below a depth of about 5 mm for the cultivated soil and below about 10 mm for the virgin. However, in the cultivated soil, resistance dramatically increased at about 40 mm depth (*i.e.* 10 mm above the base of the soil cores).

For the Cornella soils, penetration resistance increased with depth, the virgin samples tended to reach a maximum value (smaller than those of the cultivated soil) and then increase only slightly with depth. Soil resistance was again generally greater in the samples containing fine material (*i.e.* <4 mm and <0.5mm) than in those containing coarser material (*i.e.* 0.5-2 and 2-4 mm); but this difference was generally less pronounced than for the Shepparton soil. As with the Shepparton soil, the soil-resistance profile for the virgin Cornella soil fell into two distinct groups, one for coarse and one for fine aggregates. By contrast, the soil-resistance profiles for the cultivated soil were rather distinct for each aggregate size.

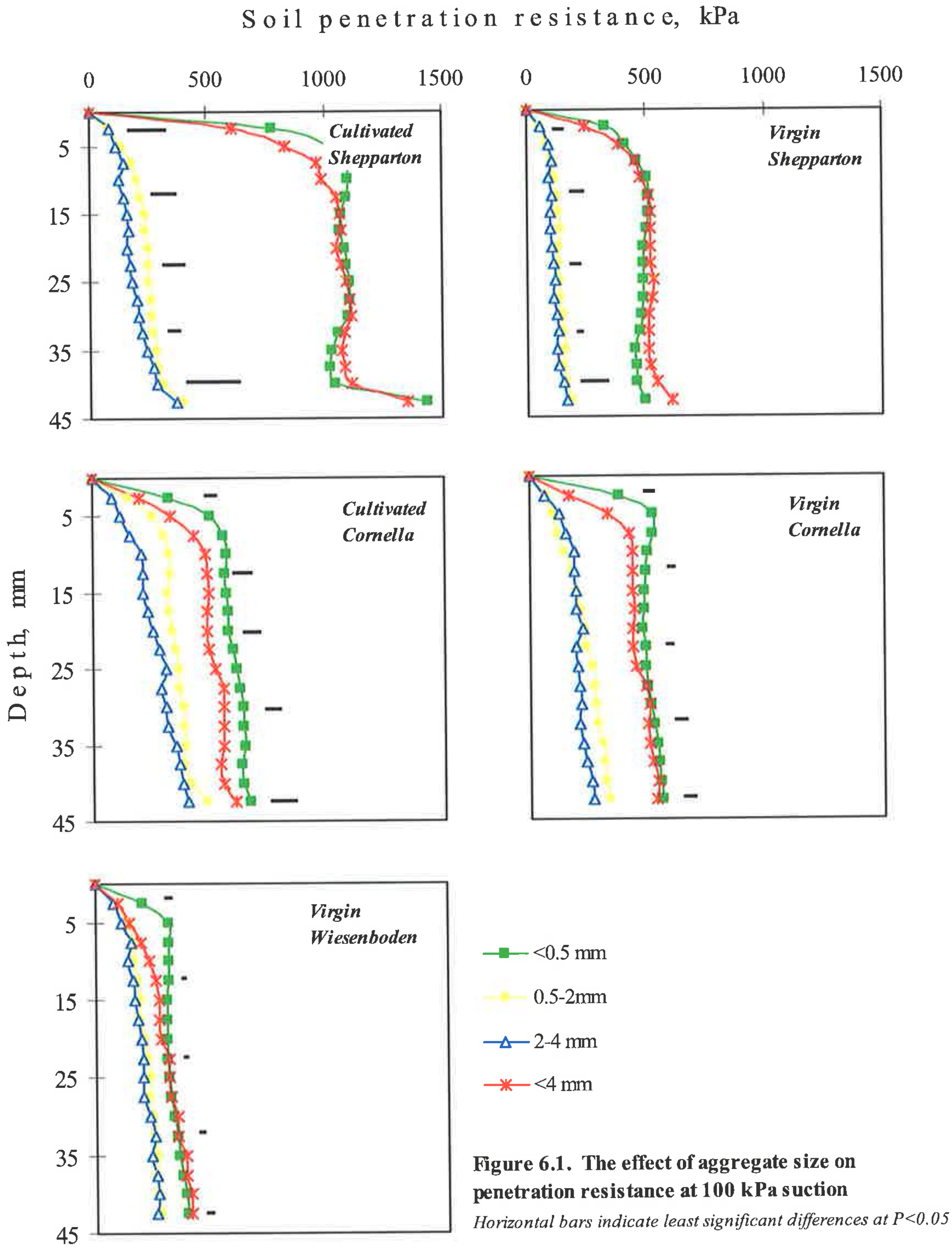

Figure 6.1. The effect of aggregate size on penetration resistance at 100 kPa suction
Horizontal bars indicate least significant differences at P<0.05

The soil resistance profiles for the Wiesenboden showed the finer aggregate size fractions having somewhat greater soil resistances than the coarser ones; that is, the <0.5 mm and <4 mm fractions clustered together with higher strengths, and the 0.5-2 mm and 2-4 mm fractions clustered together with lower strengths.

6.3.2. Bulk density

Fig. 6.2 shows the bulk densities of the soils and all values fell below 1.25 g cm^{-3}. The bulk densities of the cultivated Shepparton and Cornella soils were significantly greater than that of the virgin counterparts for all aggregate sizes. The bulk densities for aggregate sizes of <0.5 mm and <4 mm were not significantly different from each other for either soil. Similarly, there was no significant difference between bulk densities for aggregate sizes of 0.5-2 mm and 2-4 mm, although there was a general trend for the 0.5 mm to be denser than the 2-4 mm fraction.

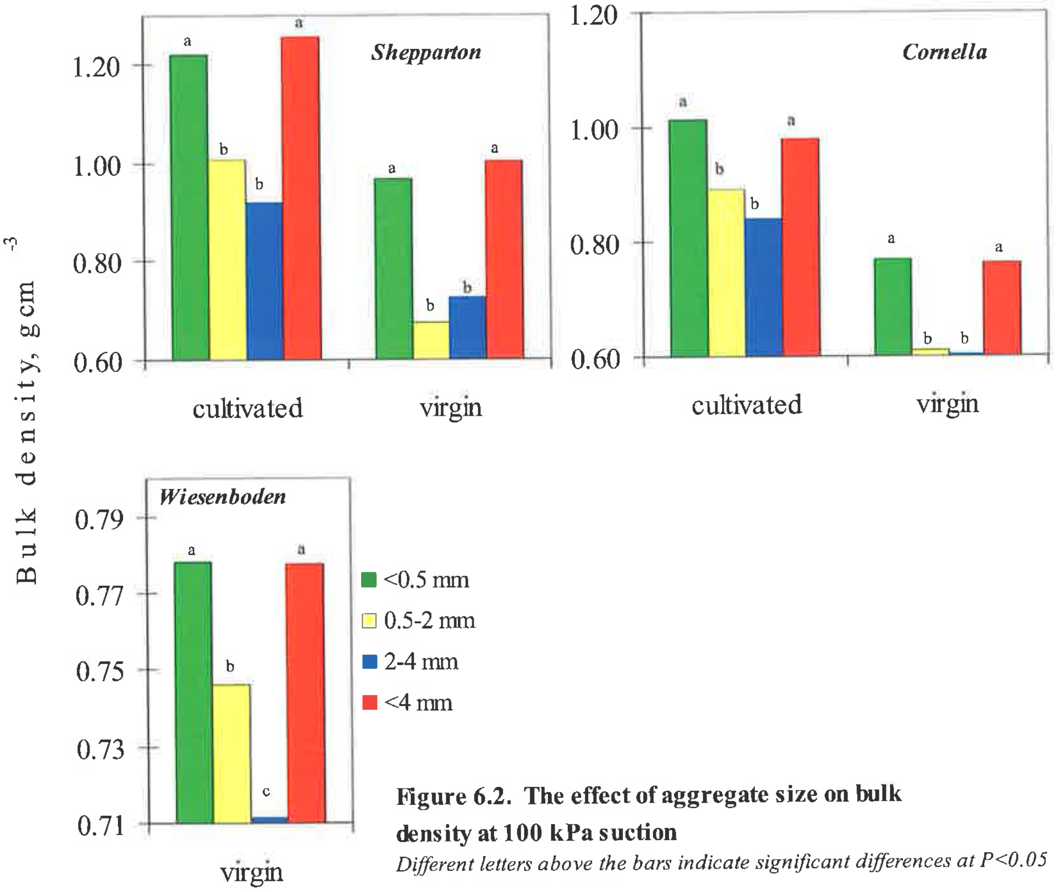

Figure 6.2. The effect of aggregate size on bulk density at 100 kPa suction
Different letters above the bars indicate significant differences at P<0.05

The bulk density of Wiesenboden for the various aggregate size fractions followed the same pattern as for the Cornella clay.

6.3.3. Water content

Table 6.1 shows water contents of the soils studied as affected by various aggregate size at 100 kPa suction. The virgin Shepparton soil invariably had higher water contents than the cultivated soil and the larger aggregate sizes tended to have higher water contents. For the other three soils, aggregate size had no significant impact on water contents at 100 kPa suction.

Table 6.1. Soil Water contents (g g^{-1}) at 100 kPa suction affected by aggregate size

Aggregate	Shepparton		Cornella		Wiesenboden
size (mm)	Cultivated	Virgin	Cultivated	Virgin	Virgin
<0.5	0.117[a]	0.154[a]	0.313[a]	0.304[a]	0.401[a]
0.5-2	0.109[a]	0.195[b]	0.300[a]	0.298[a]	0.392[a]
2-4	0.131[b]	0.203[b]	0.302[a]	0.294[a]	0.390[a]
<4	0.116[a]	0.151[a]	0.315[a]	0.307[a]	0.396[a]
LSD	0.009	0.015	0.014	0.025	0.037

In each column different letters indicate significant differences at P<0.05

6.3.4. Tensile strength

Fig. 6.3 shows the tensile strengths of the soils studied as affected by aggregate size. The aggregate size significantly affected tensile strength in both the cultivated and virgin Shepparton soils. The virgin soil had zero tensile strength at aggregate sizes of 0.5-2 and 2-4 mm as did the cultivated soil at aggregate size 2-4 mm.

The tensile strengths of all aggregate sizes of the cultivated Cornella soil were significantly greater than their virgin counterparts.

For Wiesenboden, aggregate size significantly affected the tensile strength. The value ranged from zero when the aggregate size was 2-4 mm up to 15 kPa when the aggregate size was <0.5 mm.

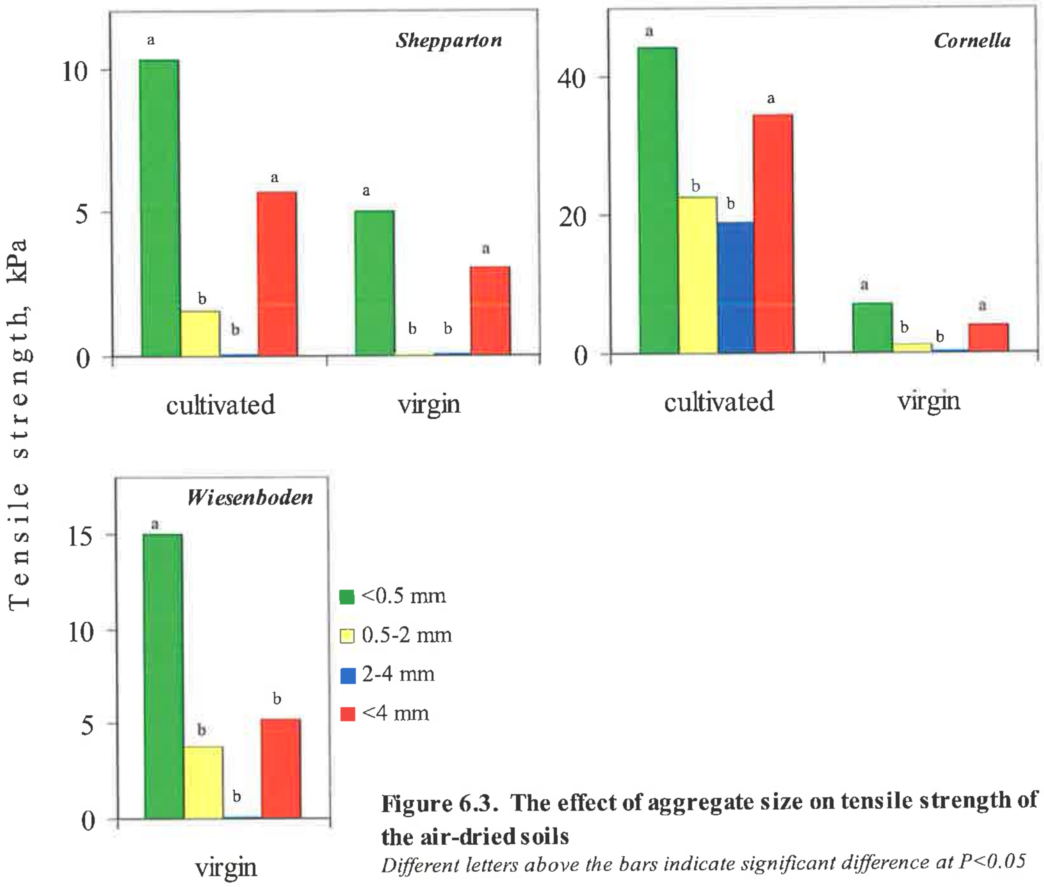

Figure 6.3. The effect of aggregate size on tensile strength of the air-dried soils
Different letters above the bars indicate significant difference at P<0.05

6.4. Discussion

Aggregate size could be expected to influence coalescence as the smaller the aggregate, the higher the exposed surface area for inter-aggregate contact. For all soils, regardless of clay content and mineralogy, the soil resistance was invariably greater for soil fractions containing finer aggregates. However, soil resistances were also consistent with the bulk densities in that the higher the bulk density, the higher the soil resistance. Increasing bulk density causes the angle of internal friction to increase (Barzegar, 1995; Bresson and Moran, 1995), resulting in higher soil cohesion (Horn, 1993) and so soil resistance. Similarly, bulk densities were always greater in soils containing less organic matter; thus the cultivated samples were always denser than the virgin samples, and the effect on the magnitude of soil resistance was usually quite large. Figure 6.4 shows the relationship between tensile strength and bulk density. All soils show strong relationships between tensile strength and bulk density. The role of organic matter in resisting structural collapse is once again implicated – it reduces the quantity of fine material and the extent of densification that occurs upon wetting/draining. The inability to separate the effects of this densification on soil strength from those of aggregate coalescence alone (*i.e.* without significant densification) underlines a major experimental challenge in this sort of project.

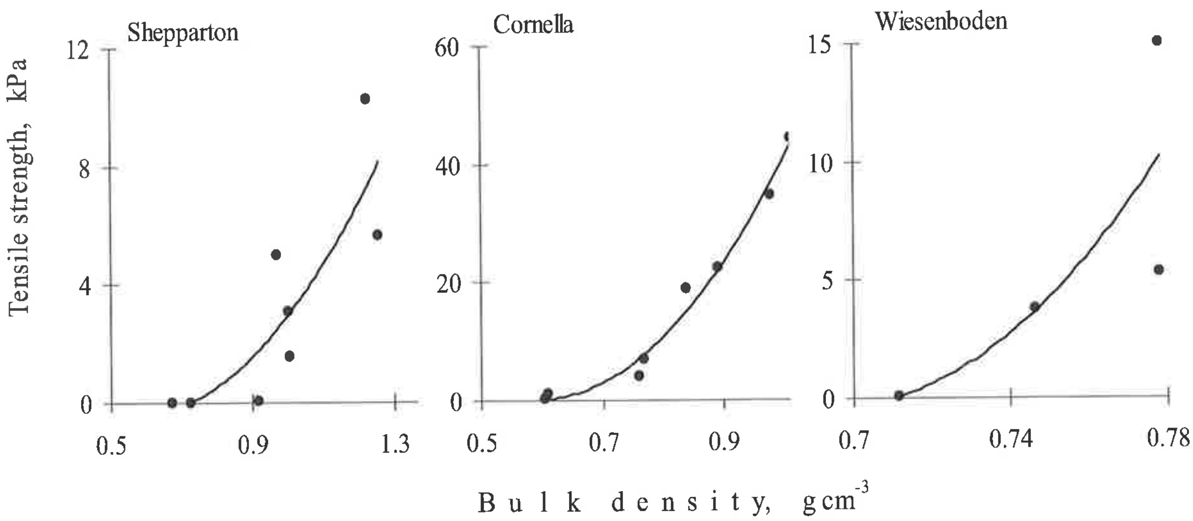

Figure 6.4. Relationships between tensile strength and bulk density

A large increase in the soil resistance toward the base of soil cores, particularly in the Shepparton soil, indicated that structural damage might have occurred in this zone as a result of rapid wetting. The structural damage to the soil aggregates at the base might protect the aggregates in the upper part of the soil cores from further damage by reducing the hydraulic conductivity and thus the wetting rate.

The differences in penetration resistances between the various aggregate sizes may reflect differences in the aggregate size distributions in the soil core samples. For example, in the cultivated and virgin Shepparton soils, the size distribution of aggregates in the <0.5 mm and <4 mm fractions was very likely indistinguishable (i.e. mostly <0.5 mm in both fractions). In the aggregate-size fractions 0.5-2 mm and 2-4 mm, there may have been a concentration of aggregates around 2 mm indicating that this size may be the most stable aggregates compared to other size in the range 0.5-4 mm.

The gravimetric water contents of different aggregate size fractions, however, depended on both clay mineralogy and organic matter content to varying degrees. For example, in the non-swelling Shepparton soil, water contents at 100 kPa suctions were greater for the virgin soils and the larger aggregate sizes, which may reflect the importance of organic matter in binding aggregates together in this soil. By contrast, for the swelling soils (e.g. Cornella), water contents were always greater in the cultivated soils and the size fractions containing finer aggregates. The differences between the swelling and non-swelling soils may reflect the relative importance of organic matter in controlling pore size distributions – being more important in non-swelling soils. The differences in water content, thus, might confound the penetrometer resistance results. Smith *et al.* (1997) developed relationships between penetrometer resistance, bulk density and water content of soils differing in textures and found that some soils, particularly those with medium and coarse textures, were more sensitive to water content.

For all soils, tensile strength was consistently related to aggregate size. The greatest value was always found for the aggregate size fraction <0.5 mm followed by that <4 mm, 0.5-2 mm and 2-4 mm. However, the relation between tensile strength and bulk density confounded any conclusions about effects of aggregate size (Figure 6.5).

The use of penetrometer resistance to distinguish the degree of aggregate coalescence may be an unreliable diagnostic tool as it is confounded by other, unavoidable experimental variables such as water content and bulk density. For example, the virgin Shepparton soil had a profoundly lower resistance but also had a lower bulk density and a much higher water content. While tensile strength of air dry soils goes part way toward addressing this problem (because it removes water content as variable), the interpretation of tensile strength data is also confounded where bulk density is a variable.

6.5. Conclusions

Aggregate size influences coalescence by exposing more surface area to coalescence when aggregates are smaller as indicated by the bulk densities being higher in the fine aggregates than in the coarse aggregates (<0.5 and <4 mm *vs.* 0.5-2 and 2-4 mm). The similarity in the penetration resistances between aggregate size <0.5 and <4 mm, and between 0.5-2 and 2-4 mm might reflect a concentration of certain aggregate sizes in those aggregate ranges. The relative importance of organic matter in controlling pore size distributions was indicated in the differences in the gravimetric water contents between the swelling and non-swelling soils – being more important in non-swelling soils. The wide range of bulk densities and water contents among the aggregate sizes confounded the use of either tensile strength or penetration resistance as effective indicators of aggregate coalescence in these experiments. Using a narrower range of aggregate sizes (i.e. 0.5-1.5 mm vs. 1-2 mm) may enable the soils to be packed into initially similar bulk density, therefore it could overcome the problem of bulk density as a variable in penetration or tensile strength measurement.

Chapter 7: Influence of wetting rate and polyvinyl alcohol (PVA) on aggregate coalescence

7.1. Introduction

Cultivation that leaves soil loose with random aggregate orientation and large pores between aggregates is prone to structural breakdown once the soil is wetted. Wetting rate is known to be one external factor that affects the degree of aggregate breakdown. Keller (1970) investigated the effect of wetting rate on loosely packed columns of unstable and relatively stable aggregates. He found that in both unstable and stable soils, increased bulk density was the result of increasing wetting rate. Wetting causes the aggregates to be weakened and allows forces such as gravity and surface tension to actively thrust the aggregates into more intimate contact forming a new structure (Kemper *et al.*, 1975). Soil conditioners such as polyvinyl alcohol (PVA) have long been used to stabilise aggregates. Many studies have shown increased aggregate stability along with improved shear strength, permeability, infiltration rate, aeration and resistance to crust formation (Allison and Moore, 1956; Stefanson, 1974; Oades, 1976; Barry *et al.*, 1991). However, little is known about the effect of wetting rate and soil conditioner, particularly PVA, on the coalescence of relatively stable aggregates. Results from previous experiments in this work showed that rapid wetting of relatively stable aggregates increases soil resistance.

The purpose of this experiment was to determine the relative effect of wetting rate, wetting extent and PVA on the coalescence of relatively water stable aggregates.

7.2. Materials and Methods

Aggregate fractions (0.5–4 mm) of two cultivated soils, Shepparton and Cornella (Chapter 2) were used in this experiment. The aggregates were divided into two samples; one sample was treated by spraying the aggregates with PVA (molecular weight = 22,000; diluted into the amount of R.O. water equal to water content at field capacity at a rate of 1.5 g/kg soil). The other sample was sprayed with R.O. water (untreated). In this way both untreated and treated soils were slowly wetted to field capacity (10 kPa suction) and then left overnight to allow the PVA to be uniformly distributed into the aggregates. The aggregates were then air dried and sieved again prior to use to obtain the same aggregate size fractions for both treatments.

The soil aggregates were packed into cylindrical rings (5 cm high and 4.77 cm i.d.) and wetted from the soil surface at different rates using a peristaltic pump. Three wetting rates were used: (i) 1 mm h^{-1} (slow), (ii) 10 mm h^{-1} (medium), and (iii) 100 mm h^{-1} (fast). All wetting events were conducted until a volume of water equivalent to field capacity (10 kPa suction) had been applied. At the end of the wetting process one group of the soil cores was left overnight at saturation (Chapter 2) and the other at field capacity by placing them on a ceramic pressure plate with a 100 cm hanging water column (Figure 2.1). The cores were then drained to 100 kPa suction (Chapter 2) for one week.

The methods used for measuring penetrometer resistance, bulk density, water content and tensile strength are presented in Chapter 2.

For each soil, a factorial design was used with PVA and wetting rate as factors and three replicates were used. Data was analysed using a Genstat 5 program (Genstat 5 Committee, 1987). If there was a significant effect at $P<0.05$, the analysis was continued with Least Significant Difference (LSD).

7.3. Results

7.3.1. Shepparton soil

Penetration resistance

Slow application of water tended to reduce soil resistance but the effects were not statistically significant at $P<0.05$ (Figure 7.1).

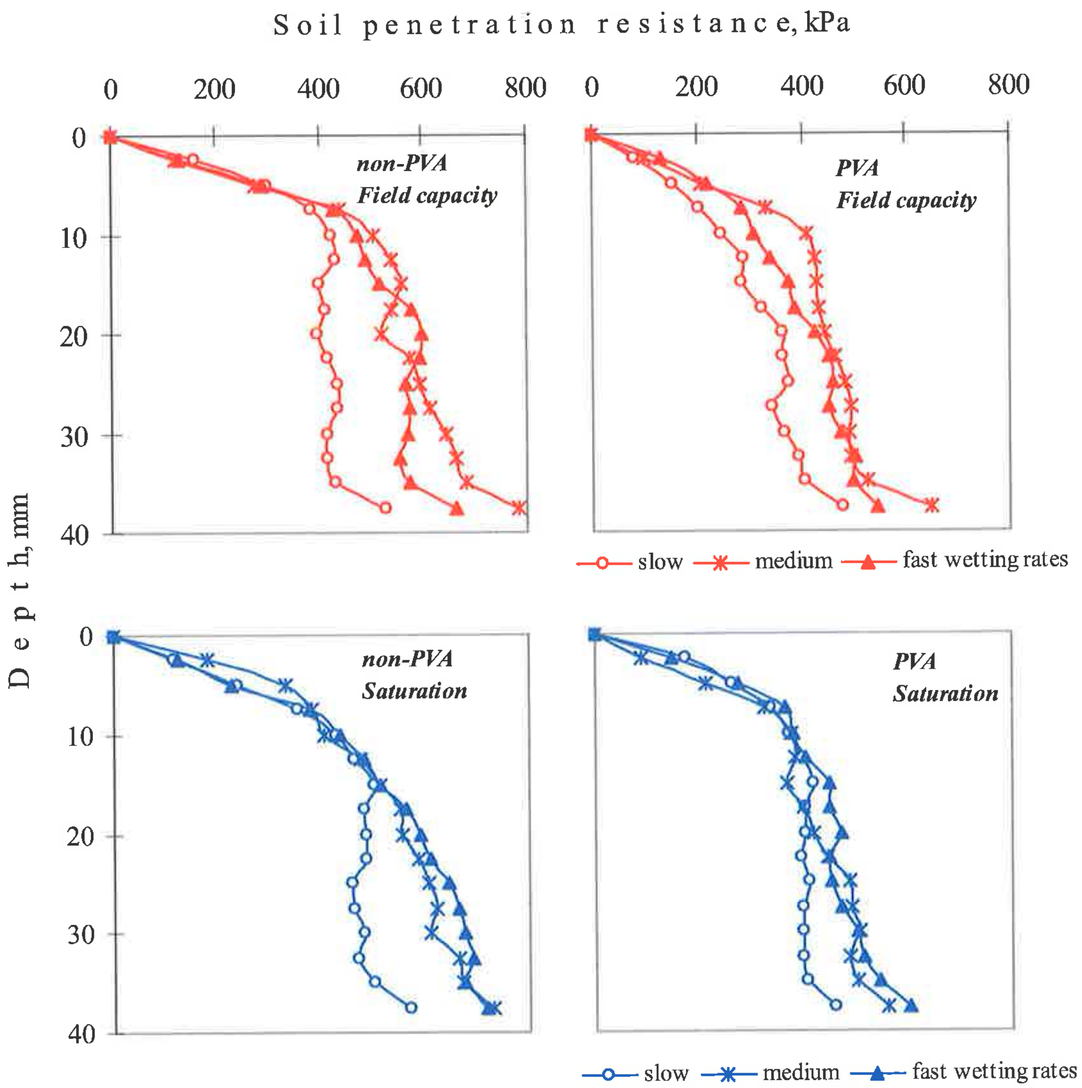

Figure 7.1. The effect of wetting rate on the penetration resistance at 100 kPa suction of Shepparton soil

Field capacity and saturation refer to the extent of wetting prior to draining to100 kPa suction

Figure 7.2 presents the soil resistance as a function of depth as affected by PVA. The application of PVA resulted in lower penetrometer resistance for all wetting rates and extents although it was not statistically significant at $P<0.05$. The reduction in penetrometer resistance varied from 9 to 41 % at 20 mm depth.

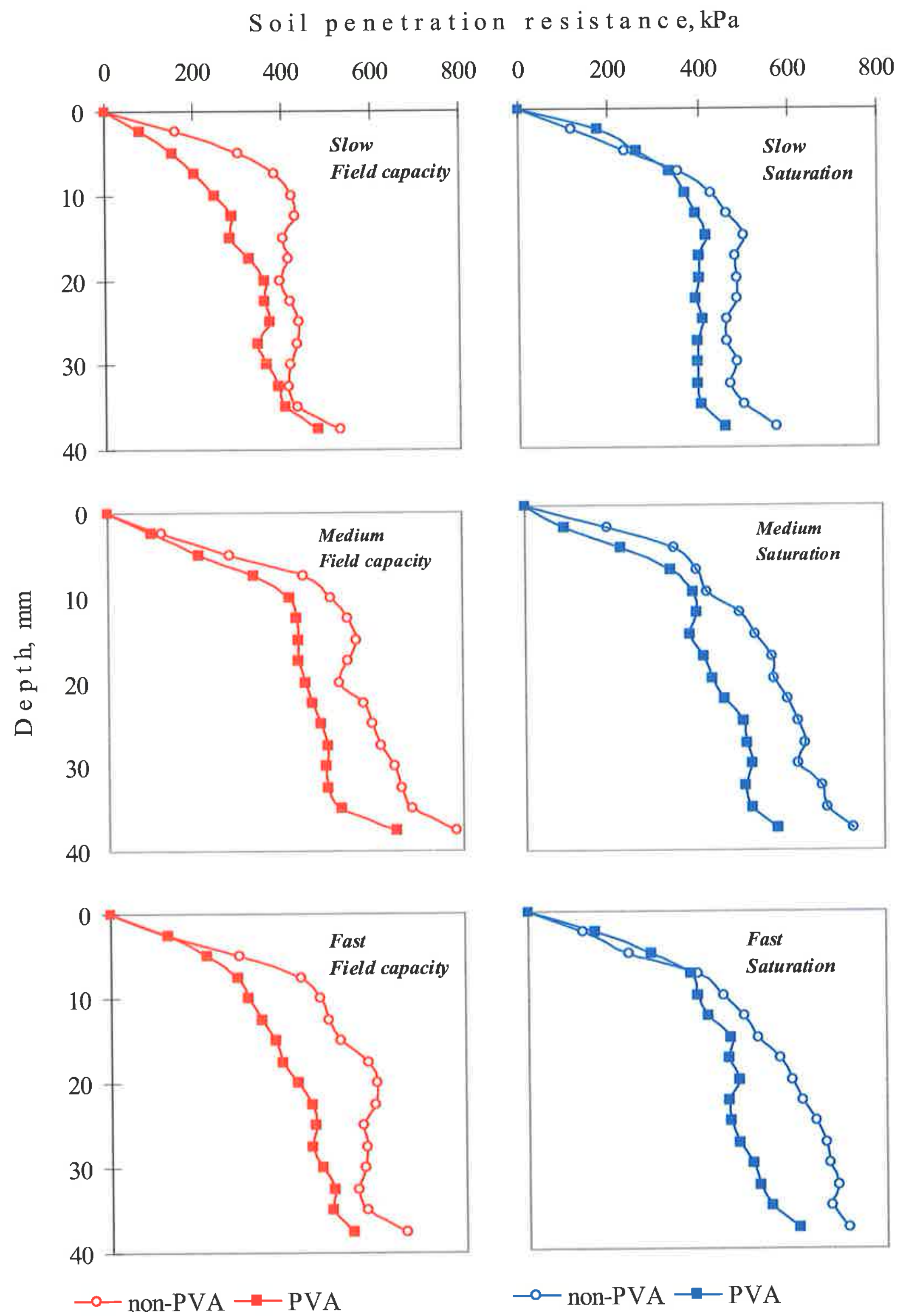

Figure 7.2. The effect of PVA on the penetration resistance at 100 kPa suction of Shepparton soil
Slow, medium and fast refer to wetting rates
Field capacity and saturation refer to the extent of wetting prior to draining to 100 kPa suction

Bulk density

Figure 7.3 shows the bulk densities of Shepparton soil as affected by wetting rate, and PVA. There was no significant effect of different wetting rates or wetting extents but the effect was significant for PVA application. For the soil that had been kept at field capacity after either slow or fast wetting, PVA decreased the bulk densities significantly, whereas for the soil that had been kept at saturation the only significant difference was found in medium wetting.

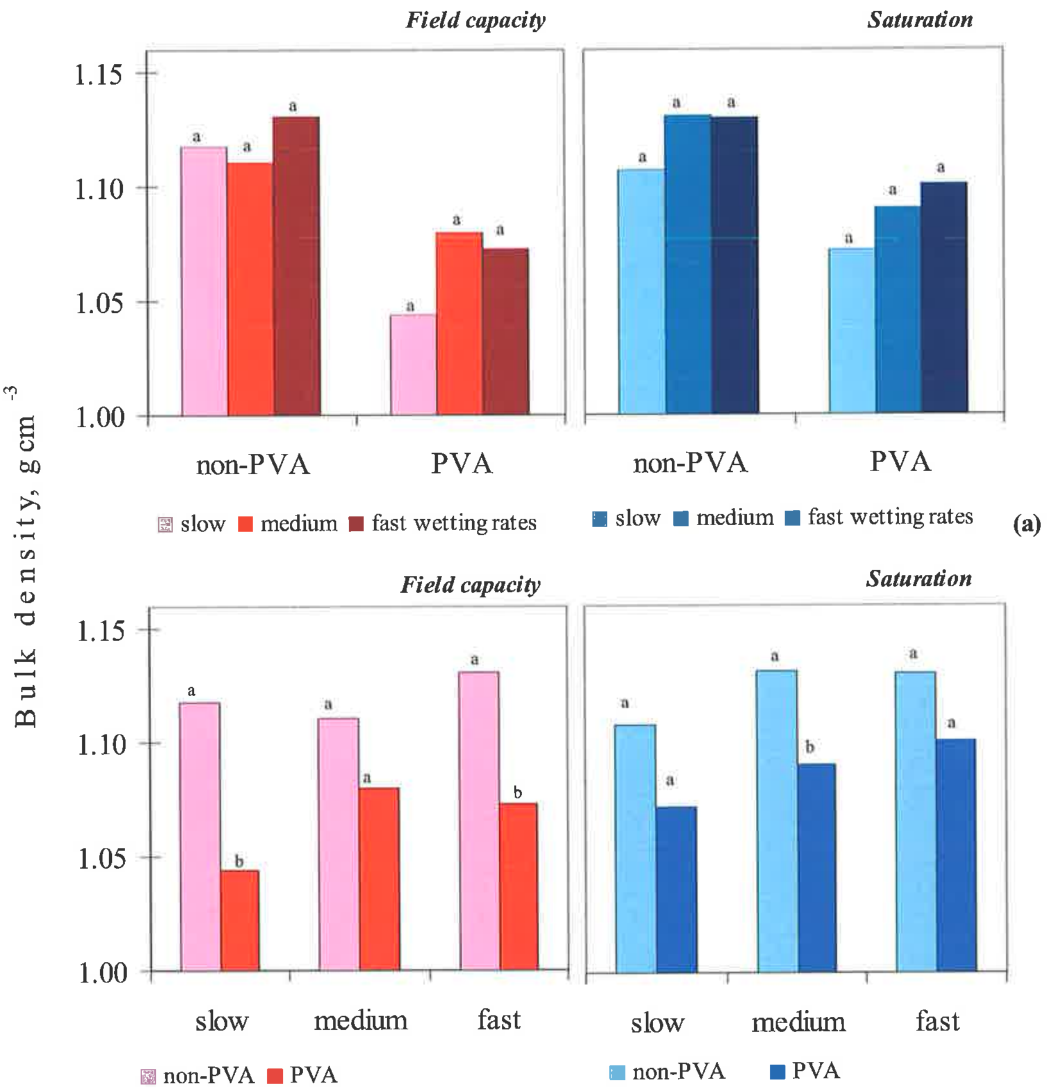

Figure 7.3. The effect of (a) wetting rate and (b) PVA on bulk density at 100 kPa suction of Shepparton soil
Different letters above the bars indicate significant differences at P<0.05
Field capacity and saturation refer to the extent of wetting prior to draining to 100 kPa suction

Water content

Table 7.1 shows the gravimetric water contents of the Shepparton soil as affected by wetting rate, wetting extent and PVA. There were no significant effects of the treatments.

Table 7.1. The effect of wetting rate, PVA and wetting extent on gravimetric water content ($g\ g^{-1}$) at 100 kPa suction of Shepparton soil

Wetting rate	Non-PVA		PVA	
	Field capacity	Saturation	Field capacity	Saturation
Slow	0.125	0.126	0.128	0.125
Medium	0.117	0.122	0.122	0.122
Fast	0.117	0.118	0.124	0.124

Tensile strength

Different wetting rates and wetting extents had significant effects on the tensile strength of Shepparton soil while the effect of PVA was not significant. Figure 7.4 shows the tensile strength of Shepparton soil as affected by wetting rate, wetting extent and PVA. As the wetting rate increased from slow to fast, the tensile strength of untreated PVA soil increased from zero to 1.7 kPa and from 0.55 to 3.4 kPa when the soil had been kept at field capacity and saturation, respectively (Figure 7.4a). The effects of wetting rates were mediated to some extent by the application of PVA. Increasing the extent of wetting from field capacity (10 kPa suction) to saturation increased tensile strength (Figure 7.4b), but mainly at the fast wetting rate. The application of PVA tended to reduce tensile strength but not in any significant way (Figure 7.4c).

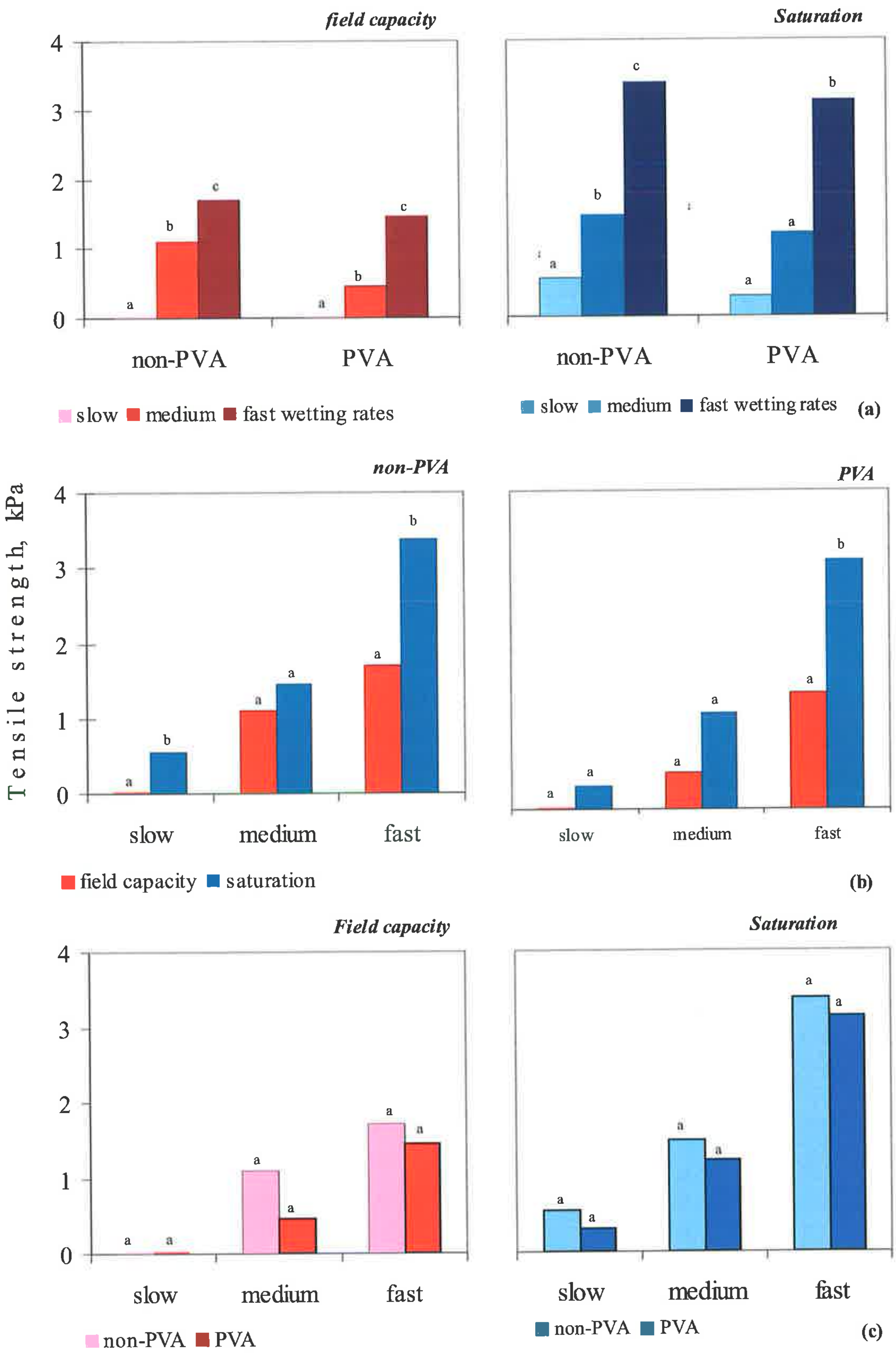

Figure 7.4. The effect of (a) wetting rate, (b) wetting extent and (c) PVA on tensile strength of the air-dried Shepparton soil

Different letters above the bars indicate significant differences at P<0.05

Field capacity and saturation refer to the extent of wetting prior to draining to 100 kPa suction

7.3.2. Cornella soil

Penetration resistance

Again, for the Cornella soil, there was no significant effect of different wetting rates, wetting extents or PVA on penetration resistance. For this soil, only the effect of wetting rate (Figure 7.5) is presented as this is the only treatment that showed a relatively clear trends in the penetration resistance. The soil resistance increased slightly with increasing wetting rate from slow to fast. This result was more pronounced when the soil was not treated with PVA and the wetting extent was at field capacity.

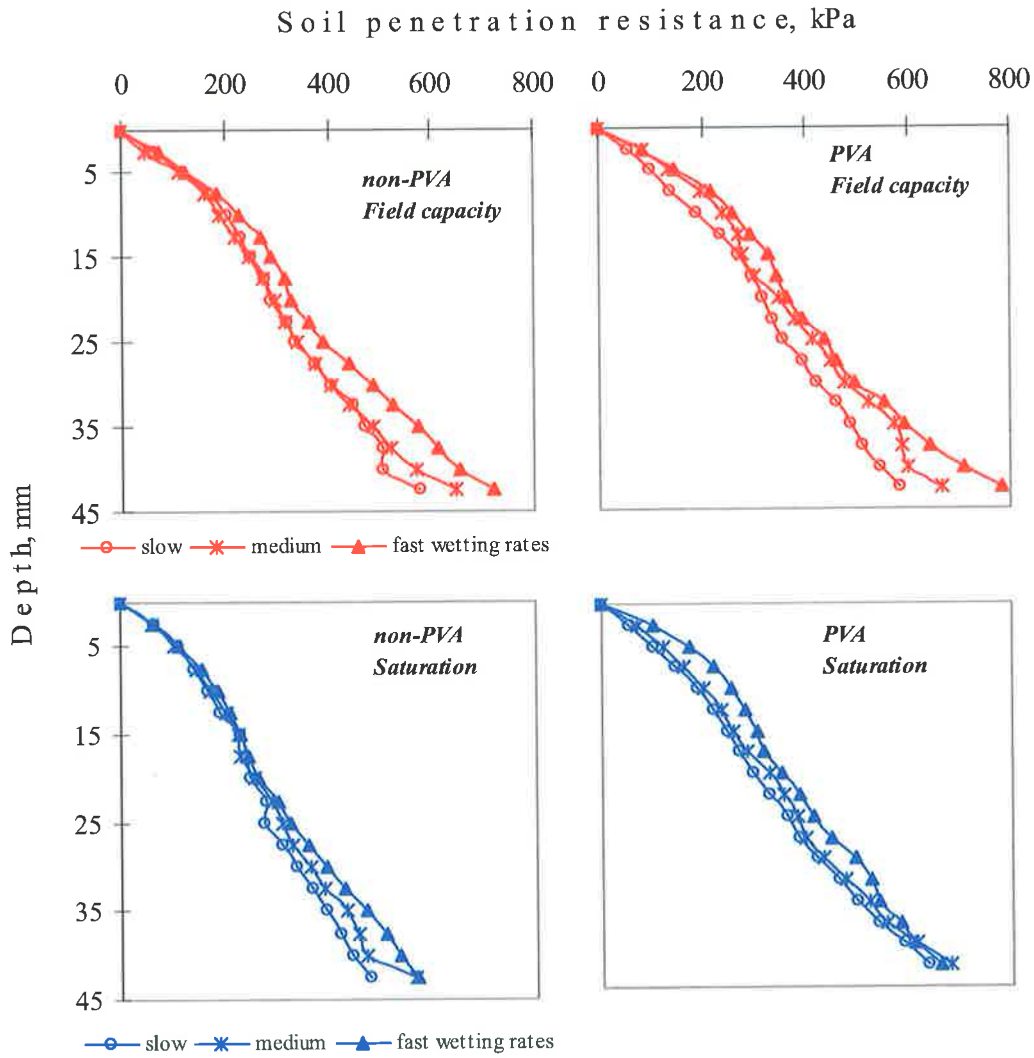

Figure 7.5. The effect of wetting rate on penetration resistance at 100 kPa suction of Cornella soil
Field capacity and saturation refer to the extent of wetting prior to draining to 100 kPa suction

Bulk Density

Figure 7.6 shows the bulk densities of Cornella soil as affected by wetting rate, and PVA. Although the effects were not generally statistically significant at P<0.05, increased wetting rates tended to increase bulk density slightly while soil treated with PVA appeared to have higher bulk density than untreated soil at all wetting rates and extents.

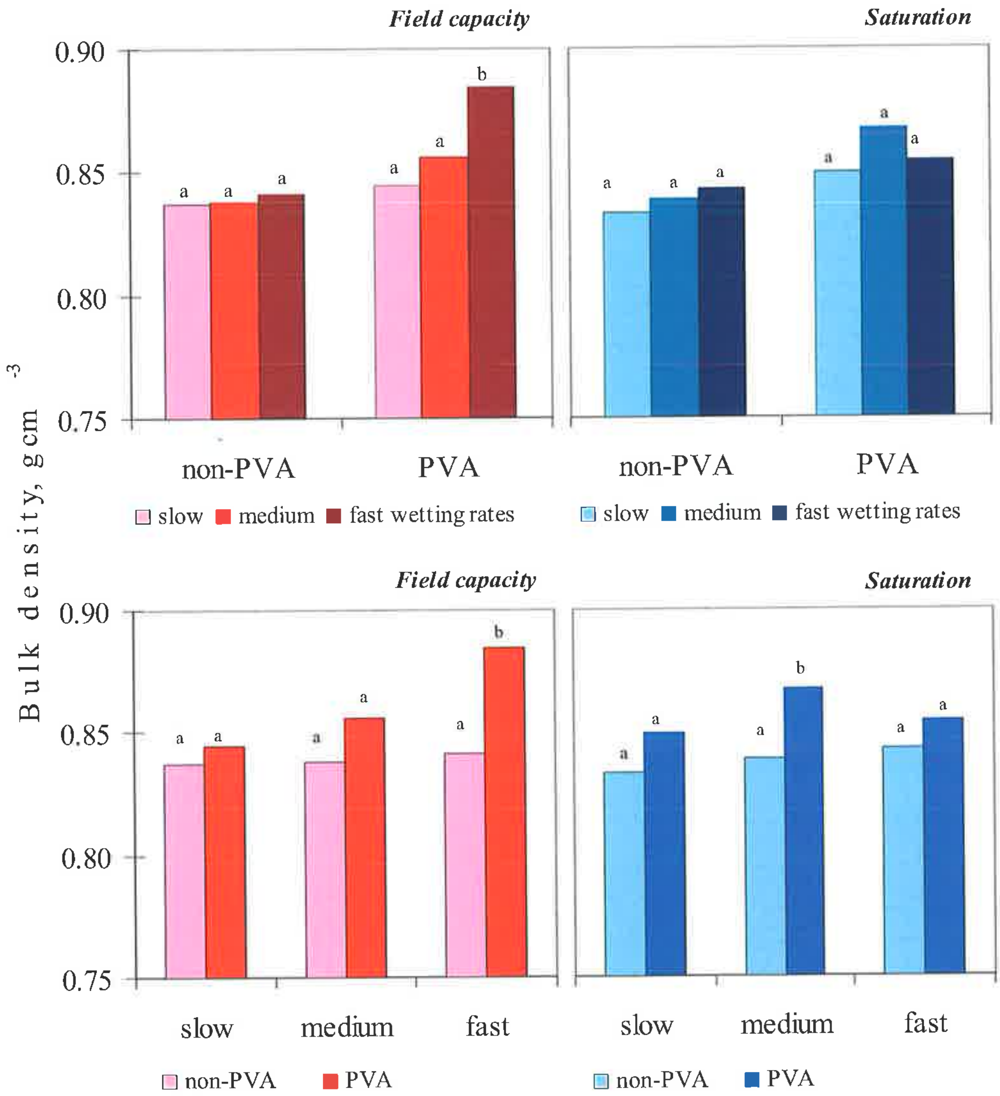

Figure 7.6. The effect of (a) wetting rate and (b) PVA on bulk density at 100 kPa suction of Cornella soil
Different letter above the bars indicate significant differences at P<0.05
Field capacity and saturation refer to the extent of wetting prior to draining to 100 kPa suction

Water content

Table 7.2 shows the gravimetric water content of the Cornella soil as affected by wetting rate, wetting extent and PVA.

Table 7.2. The effect of wetting rate, wetting extent and PVA on gravimetric water content ($g\ g^{-1}$) at 100 kPa suction, for Cornella soil.

Wetting rate	Non-PVA		PVA	
	Field capacity	Saturation	Field capacity	Saturation
Slow	0.320	0.309	0.300	0.310
Medium	0.326	0.320	0.308	0.312
Fast	0.317	0.319	0.298	0.318

Although the effects were not significant, soil treated with PVA generally had lower water contents.

Tensile strength

Figure 7.7 shows the effect of wetting rate, wetting extent and PVA on tensile strength of Cornella soil. Increasing wetting rate increased the tensile strength significantly in either untreated or treated PVA soil. Soil treated with PVA tended to have significantly lower tensile strength than untreated soil.

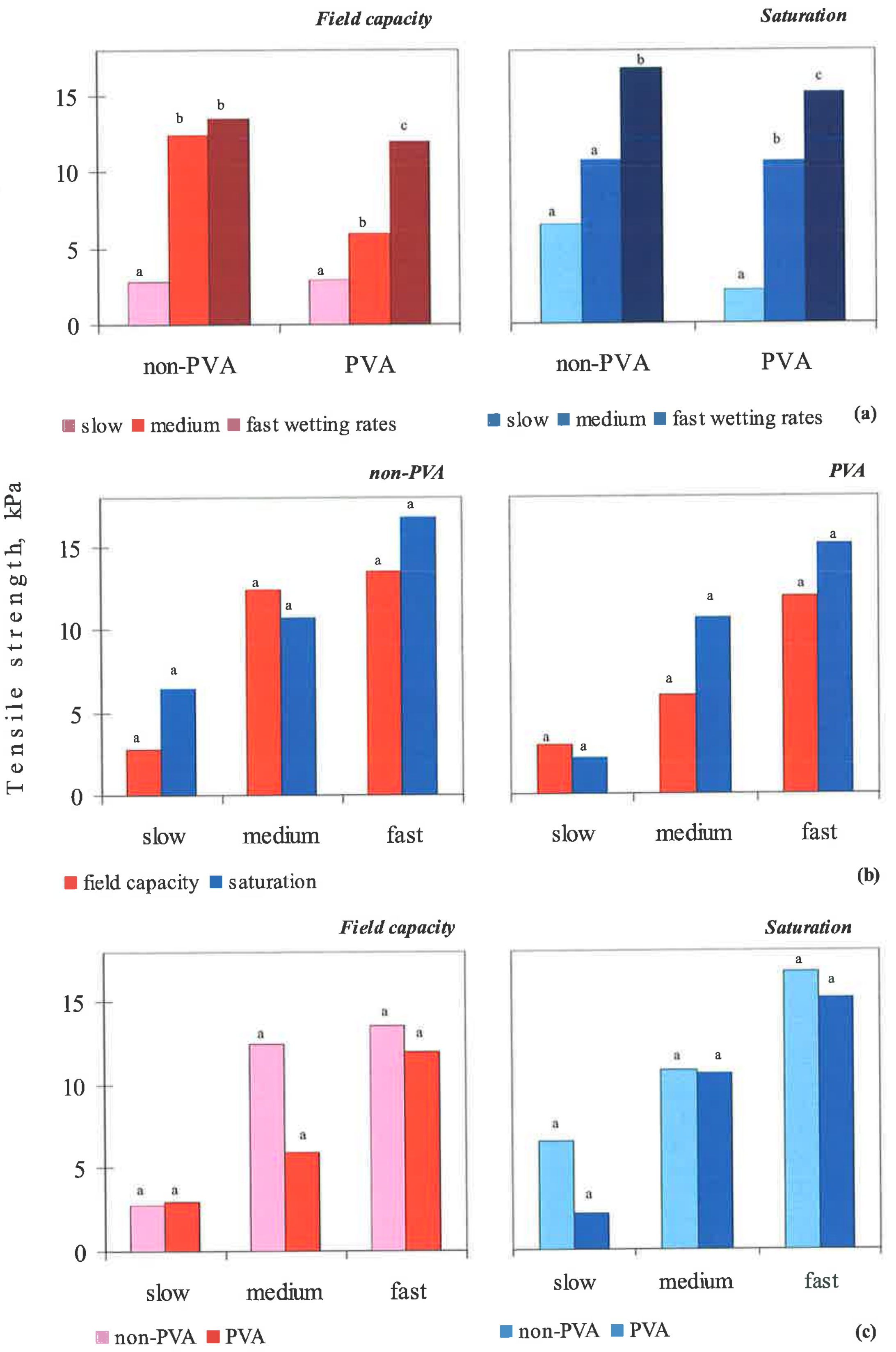

Figure 7.7. The effect of (a) wetting rate , (b) wetting extent and (c) PVA on tensile strength of air-dried Cornella Soil

Different letters above the bars indicate significant differences at P<0.05

Field capacity and saturation refer to the extent of wetting prior to draining to100 kPa suction

Slow, medium and fast refer to wetting rates

7.4. Discussion

The effect of wetting rate, extent of wetting and PVA was more pronounced in the Shepparton than the Cornella soil in terms of soil resistance and bulk density. According to Kemper *et al.* (1975) the degree to which aggregates break down is determined by the bonding strength within the aggregates and the rate of soil wetting. The increase in penetrometer resistance in Shepparton soil as a result of increased wetting rate was often accompanied by a small increase in bulk density indicating that rapid wetting may have caused some disintegration of the aggregates due to incipient failure (Quirk and Panabokke, 1962). This phenomenon in the Cornella soil was not as obvious as in the Shepparton soil as the penetration resistances were very similar between wetting rates.

Application of PVA always reduced the soil resistance in the Shepparton soil but produced little change in the Cornella soil. It appeared that the use of PVA is more effective in coarse-textured soil (Shepparton) than clay soil (Cornella). However, PVA may only affect the soil resistance in the Shepparton soil indirectly as the bulk densities also decreased accordingly. When PVA solution is added to a soil, the PVA molecules will diffuse into the pores according to the suction under which it is applied. Quirk and Williams (1974) showed that the application of PVA to the soil will stabilise the pores occupied by the PVA upon drying; in their experiment the stabilised pores were of 30 μm diameter or less as the PVA was added at field capacity (10 kPa suction). This in turn might reduce the effect of incipient failure (Quirk and Panabokke, 1962) of the aggregates when they are wetted rapidly.

Both the Cornella and Shepparton soils showed similar results in terms of tensile strength, although the magnitude was lower in the Shepparton soil due to its lower clay content. The tensile strength increased with increasing wetting rate and wetting extent but decreased with the addition of PVA. The increase in tensile strength indicated that aggregate coalescence had progressively developed as a result of increased wetting rate and extent of wetting while PVA retarded this development.

7.5. Conclusions

The effect of PVA and wetting rate on soil penetrometer resistance was more pronounced in coarse-textured soil (cultivated Shepparton fine sandy loam) than in a clay soil (cultivated Cornella clay). PVA may have affected the penetration resistance of the Shepparton soil indirectly by reducing its bulk density. Both Shepparton and Cornella soils showed similar trends in tensile strength in which it increased with increasing wetting rate and wetting extent but decreased with the addition of PVA. Increasing rate of wetting might increase the rate and amount of soil materials exchange between aggregate at their point of contacts while PVA might coat the exterior part of aggregates minimising the development of aggregate coalescence by limiting materials exchanged between the aggregates

Chapter 8 : The effect of sodicity on soil aggregate coalescence

8.1. Introduction

Sodicity is well known as a major problem in agricultural lands in semi-arid and arid regions of the world. It affects the relationships of soil-water-air to such an extent that the soil is difficult to work under wet and dry conditions and greatly restricts root growth (Rengasamy and Olsson, 1991) due to physical and chemical constraints. An exchangeable sodium percentage (ESP)>15 has been considered as the threshold above which soil structure is adversely affected (U.S. Salinity Laboratory, 1954). In Australia the deleterious effect of sodicity may occur at much lower ESP and the threshold is defined as ESP>6 (Northcote and Skene, 1972; Emerson and Chi, 1977; Isbell, 1996). Most studies on the effect of sodicity on soil structure have been done using saturated hydraulic conductivity (e.g. Rhoades and Ingvalson, 1969; McIntyre, 1979; Shainberg *et al.*, 2001). The strength of remoulded soils has been found to consistently increase with clay content and clay dispersion (Barzegar *et al.* 1994, 1995), but less attention has been given to the strength of natural aggregates, which is the main focus of this experiment.

In the work described here, a range of ESPs was chosen to cover the range below and above the threshold ESP value of 6. The objective of this experiment was to investigate the effect of sodicity on aggregate coalescence.

8.2. Material and Methods

8.2.1. Soil

Air-dried aggregate fractions of 0.5-2 mm from four soils were used in this experiment, including Cornella clay (virgin and cultivated), Shepparton sandy loam (virgin and cultivated), Wiesenboden (virgin), and Rhynie clay (cultivated) soils.

Soil pre-treatment

The following process was designed to alter soil ESP of otherwise intact natural aggregates. Soil aggregates were initially pre-treated to achieve ESP values of virtually zero, 5 and 10. Following the method of Suriadi (2001), 350 – 450 g of each soil was placed on a sintered glass funnel (porosity 4; 10 cm inner diameter, 6 cm depth from the funnel rim to the sintered plate). The funnel was connected to a 125 cm-long vinyl tube (16 mm i.d.). The soil was wetted slowly (to avoid any damage to the natural soil aggregates) with 0.1 M $CaCl_2$ initially at 10 kPa suction and then gradually wetted until the whole soil was immersed in the solution. The use of 0.5-2 mm aggregates (without including finer material <0.5 mm) caused the wetting process to take a long time due to the unavoidably poor inter-aggregate contact and between the soil aggregates and the sintered glass plate; up to 10 weeks were needed to fully immerse the soil in the $CaCl_2$ solution for the first time. The soil was then left for 24 h and then drained to 10 kPa suction. Once the aggregates had been thoroughly wetted, the process became faster. This process was repeated 3 times before the solution was removed and replaced with fresh 0.1 M $CaCl_2$ solution and the whole process repeated. This whole process was then repeated with distilled water (7 times) to remove excess electrolyte and to achieve relatively low electrical conductivity (EC) of the soil water comparable to that of R. O water. The soil was then air dried and placed back onto the sintered glass funnel ready to be treated with different concentrations of NaCl solution to achieve ESP 0 (R.O water), 5 and 10 (Table 8.1). The concentrations of sodium required to establish various ESP values in the soils once they were calcium saturated were calculated from estimated values of the Gapon constant for each soil (Suriadi, 2001), estimated values of the cation exchange capacity of the soils (these had not yet been measured at this stage) and the ratio of soil:solution employed in the sintered funnels (about 1:4).

Table 8.1. Sodium solution concentrations (mmol NaCl L^{-1}) applied once to various calcium-saturated soils to achieve ESP 0, 5 and 10

Soil	ESP 0	ESP 5	ESP 10
Cultivated Shepparton	0	13	35
Virgin Shepparton	0	11	30
Cultivated Cornella	0	40	100
Virgin Cornella	0	31	79
Rhynie	0	36	91
Wiesenboden	0	33	65

As in the process of saturating soil with exchangeable Ca^{2+}, the same process was applied once with a Na^{+} solution to achieve the desired ESP, then rinsed with R.O. water. However, it was not possible to attain a relatively low electrical conductivity for some soils, particularly the ones that had been treated to achieve higher ESP. Once clay dispersion was apparent the rinsing process was ceased.

It was not possible to avoid clay dispersion when the soils were rinsed with R.O. water following the application of the Na^{+} solution to the soils. For example, the cultivated Cornella clay showed severe clay dispersion once the highest ESP sample was rinsed with water; this suggested that subsequent rinsing may be counter-productive. Other soils were able to be rinsed several times before clay dispersion become apparent. This resulted in various electrolyte conductivity values for the different soil samples (Table 8.2).

Table 8.2. The electrical conductivity (dS/m) of the soils studied (1:5) after pre-treatment with NaCl solutions

Soil	Intended ESP		
	0	5	10
Cultivated Shepparton	0.05	0.05	0.10
Virgin Shepparton	0.04	0.05	0.08
Cultivated Cornella	0.07	0.11	0.33
Virgin Cornella	0.06	0.11	0.30
Rhynie	0.08	0.09	0.15
Wiesenboden	0.12	0.15	0.44

Soil analysis after pre-treatment showed that the intended ESP was not always achieved. This is because the Gapon constants of the soils were only estimated based on experiences in this laboratory (by reference to Suriadi, 2001). Table 8.3 shows that the intended ESP 0 ranged from 0.7 to 1.4. As the process of achieving these different levels of sodicity needed a relatively long period of time due to the slow process of wetting, it was unlikely that zero sodicity could be achieved due to the buffering effects resulting from mineral weathering and hydrolysis (Rengasamy, 1983). Similarly the intended ESP 5 varied from 3.4 to 7.1 and ESP 10 from 5.4 to 14.1.

Table 8.3. Actual ESP of the soils studied after pre-treatment

Soil	Intended ESP		
	0	5	10
Cultivated Shepparton	0.8	5	10.8
Virgin Shepparton	0.7	5.2	8.2
Cultivated Cornella	1.4	7.1	13.9
Virgin Cornella	0.8	6.6	14.1
Rhynie	0.7	4.8	10.9
Wiesenboden	1	3.4	5.4

The soil was once again air dried and sieved to obtain 0.5–2 mm aggregates before packing them into the cylindrical rings.

Soil packing, wetting and physical measurements

For penetrometer resistance measurements, approximately 50 g and 70 g of sieved, air-dry soil aggregates (0.5-2 mm) of virgin and cultivated soil, respectively, were packed into rings (5 cm high, 4.77 cm i.d.) with a thin mesh at the base whereas for tensile strength measurement, approximately 15 g and 20 g of virgin and cultivated soils, respectively, were packed into smaller rings (3.8 cm high, 3 cm i.d.). Soil wetting was carried out at near saturation and then drained at 100 kPa suction (Chapter 2). The methods used for measuring penetrometer resistance, bulk density, water content and tensile strength are presented in Chapter 2.

8.2.2. Experimental design

For each soil, a completely randomised design was used with three replicates. The treatments were the levels of sodicity (ESP). Data was analysed using a Genstat 5 program (Genstat 5 Committee, 1987).

8.3. Results

8.3.1. Penetration resistance

Fig. 8.1 shows the penetration resistance of the soil studied as a function of depth with different levels of sodicity. In the following discussion the level of intended ESP values of 0, 5 and 10 will be referred to as low, medium and high, respectively.

In general, the penetration resistance of the virgin Shepparton soil was always lower than the cultivated soil. In the cultivated Shepparton, at a depth of 15 mm the soil resistance progressively increased from 166 kPa up to 406 kPa with increasing sodicity from low to high. For the virgin Shepparton, the soil resistance was similar for low and medium ESP but tended to increase when the sodicity was high.

The virgin Cornella soil also showed a greatly reduced (~50%) penetration resistance compared to its cultivated counterpart. Although the penetrometer resistance of both soils showed similar trends in responding to sodicity; this trend was weaker for the Cornella soils. However, it appears that the virgin soil was more susceptible to sodicity than its counterpart as shown by a significant increase in resistance when the ESP was increased from low to medium. The penetrometer resistances were similar for medium and high ESP.

Rhynie soil showed that up to 38.5 mm depth there was a significant reduction of resistance with increasing sodicity from low up to high. However, beyond this depth the resistance of soil with medium ESP appeared to be the largest.

The trend in soil resistance as affected by sodicity for virgin Wiesenboden was very similar to that of cultivated Rhynie soil but smaller in magnitude. Increasing sodicity from low to high tended to decrease the soil penetrometer resistance up to a depth of 32.5 mm. Beyond this depth, the penetrometer resistance of soil with medium ESP was higher than those soils having low and high ESP. The penetrometer resistance of soil with high ESP exceeded that of soil with low ESP at depths larger than 34 mm.

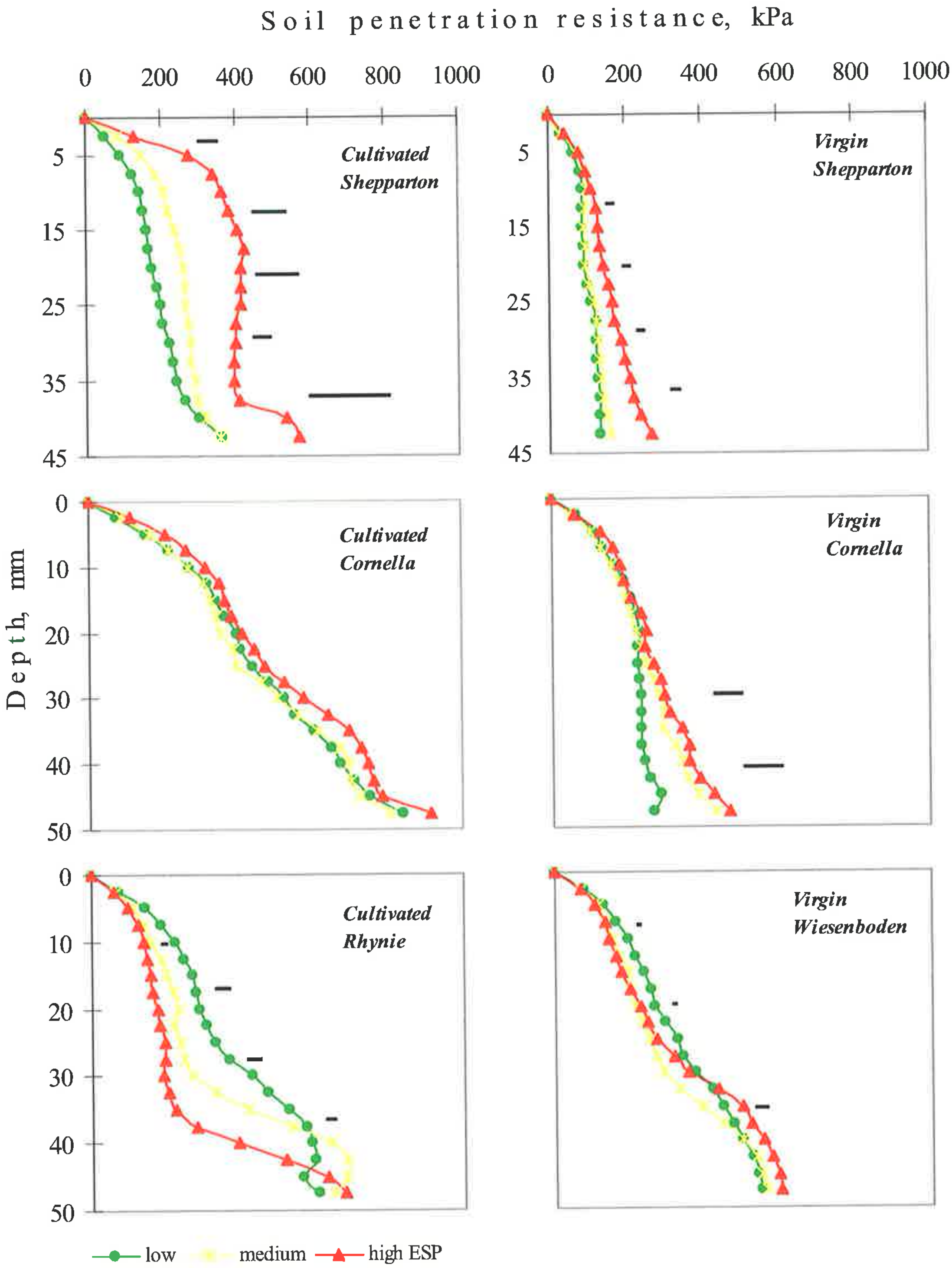

Figure 8. 1. The effect of sodicity on penetration resistance at 100 kPa suction
Horizontal bars indicate least significant differences at P<0.05

8.3.2. Bulk Density

Fig. 8.2 shows the bulk densities of the soils studied as affected by sodicity. In general, the virgin Shepparton soil showed a much lower bulk density than the cultivated soil; however, both soils showed significant increases with increasing sodicity. The bulk density in the cultivated soil increased from 1.03 to 1.10 g cm^{-3} when the sodicity increased from low to high whereas in the virgin soil the bulk density increased from 0.81 to 0.85 g cm^{-3}. The increase in bulk density indicated the instability of the soil aggregates due to increasing sodicity.

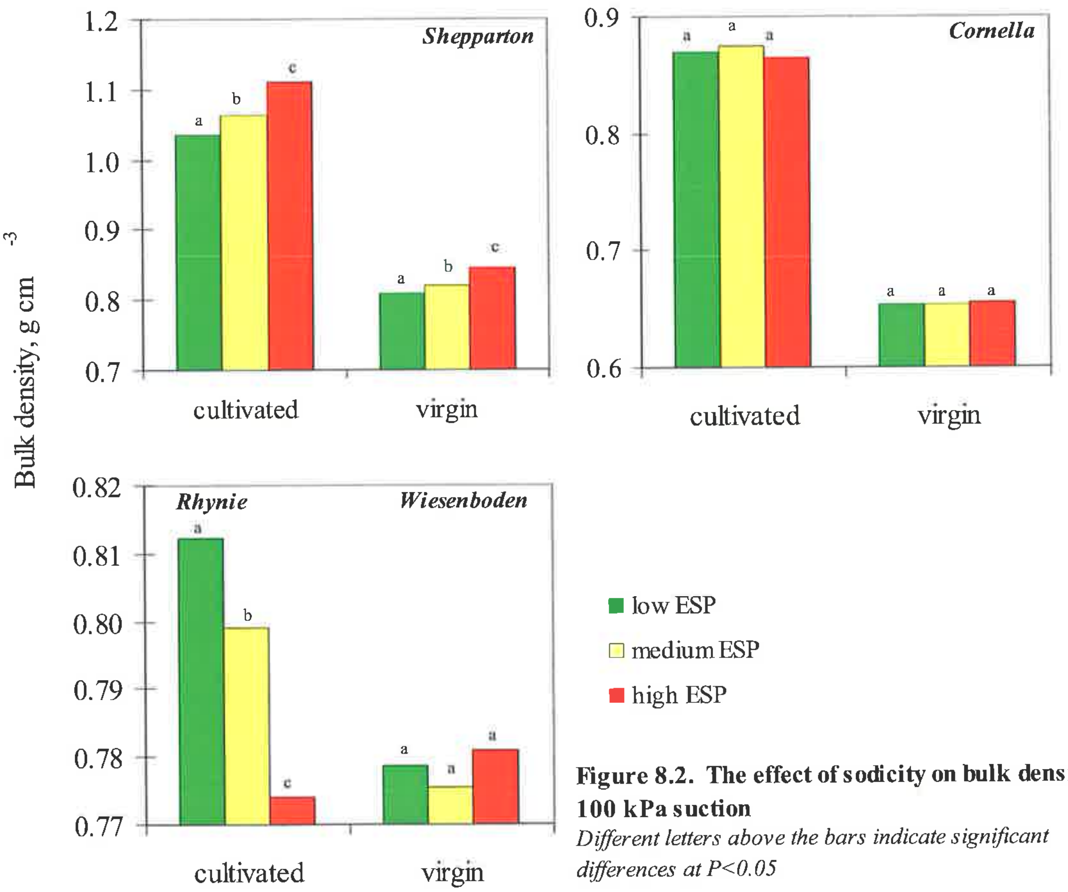

Figure 8.2. The effect of sodicity on bulk density at 100 kPa suction
Different letters above the bars indicate significant differences at P<0.05

The effect of sodicity on bulk density was not significant for either the cultivated or virgin Cornella soil. The cultivated Rhynie soil showed a consistent decrease in bulk density from 0.81 to 0.77 g cm^{-3} with increasing sodicity. The decrease in the bulk density of this soil resulted from an increase in the swelling of this clay soil. The effect of sodicity on the bulk density of Wiesenboden was found to relatively constant for all ESP values.

8.3.3. Water Content

The effect of sodicity on gravimetric and volumetric water content of the soils studied is presented in Table 8.4 and 8.5.

Table 8.4. Gravimetric water contents (g g^{-1}) at 100 kPa suction as affected by sodicity

ESP	Shepparton		Cornella		Rhynie	Wiesenboden
	Cultivated	Virgin	Cultivated	Virgin	Cultivated	Virgin
Low	0.108^a	0.209^a	0.300^a	0.339^a	0.277^a	0.379^a
Medium	0.110^a	0.207^a	0.314^b	0.356^b	0.396^b	0.394^b
High	0.109^a	0.214^a	0.306^a	0.349^a	0.440^c	0.401^b
LSD	na	na	0.005	0.013	0.019	0.006

In each column, different letters indicate significant differences at P<0.05
na, not applicable

Table 8.5. Volumetric water contents (cm^3 cm^{-3}) at 100 kPa suction as affected by sodicity

ESP	Shepparton		Cornella		Rhynie	Wiesenboden
	Cultivated	Virgin	Cultivated	Virgin	Cultivated	Virgin
Low	0.120^a	0.169^a	0.261^a	0.222^a	0.225^a	0.295^a
Medium	0.117^b	0.170^a	0.275^b	0.233^b	0.316^b	0.306^b
High	0.121^c	0.181^a	0.265^a	0.229^a	0.341^c	0.313^b
LSD	0.0035	na	0.009	0.011	0.016	0.012

In each column, different letters indicate significant difference at P<0.05
na, not applicable

Water contents at 100 kPa suction increased modestly with sodicity, for the cultivated Shepparton and both the Cornella soils. Large significant increases occurred for the Rhynie and Wiesenboden soils.

8.3.4. Tensile Strength

Figure 8.4 shows the effect of sodicity on tensile strength of the air-dried soils. There is a small but significant increase in tensile strength of cultivated Shepparton soil (from zero to 5 kPa when the ESP increased from low to high). The virgin Shepparton soil had zero tensile strength at all ESP values.

Increasing sodicity also consistently increased the tensile strength of the cultivated Cornella soil from 15 to 20 kPa as the ESP increased from low to high. As for the Shepparton soil, the virgin Cornella soil also had zero tensile strength. The soil cores crumbled during even careful handling.

The cultivated Rhynie soil showed a very significant increase ($P<0.01$) in tensile strength with increasing sodicity. The tensile strength increased dramatically from only 48 to 355 kPa when the soil ESP increased from medium to high.

The increase in tensile strength of virgin Wiesenboden soil was found to be significant ($P<0.05$) with increasing sodicity. The tensile strength increased from 33 to 58 kPa when the ESP increased from low to high.

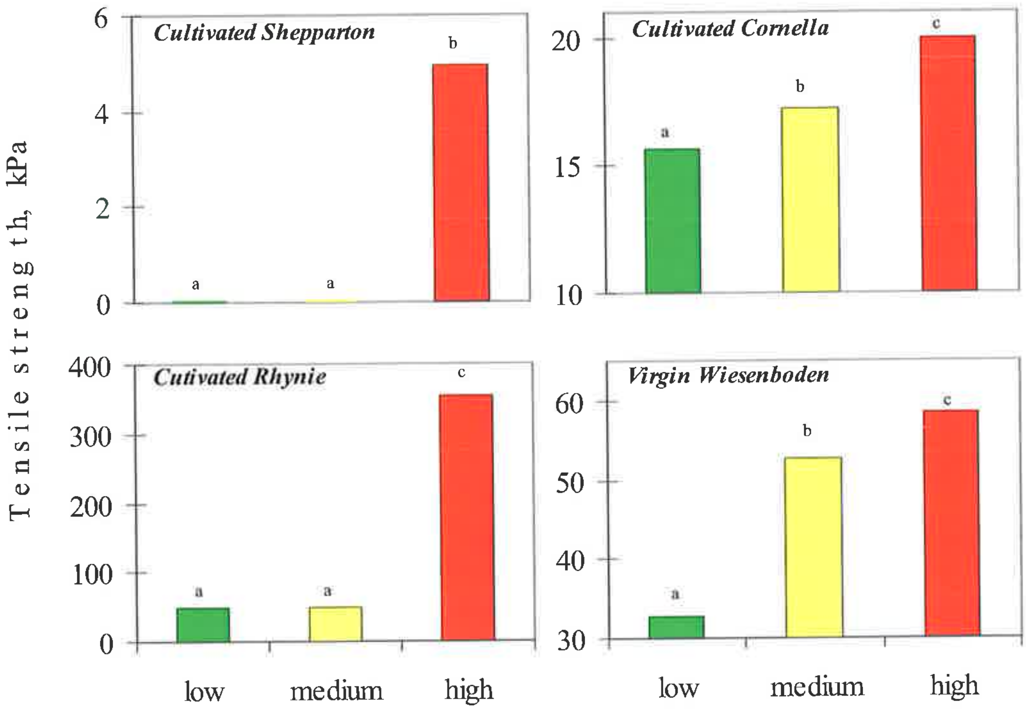

Figure 8. 3. The effect of sodicity on tensile strength of the air-dried soils studied
Vertical bars indicate significant difference at P<0.05

8.4. Discussion

8.4.1. Shepparton soils

In the cultivated and virgin Shepparton soils, increasing sodicity enhanced soil aggregate coalescence as shown by the significant increase in soil penetrometer resistance. However, the increase in penetrometer resistance was also accompanied by significant increases in soil bulk densities. This suggested that the effect of sodicity on aggregate coalescence in these soils might involve two mechanisms: (i) failure of soil aggregates (Quirk and

Schofield, 1955) and (ii) clay dispersion (Abu-Sharar *et al.*, 1987). Aggregates may fail mechanically from either the internal swelling pressures rupturing them, or from the local shearing stresses deforming the weakened aggregates, or from combination of both mechanisms (Waldron and Constantin, 1968) resulting in slaking of macroaggregates (>250 μm) into microaggregates (20-200 μm) (Oster and Shainberg, 1979). This may have resulted in more aggregate coalescence as the number and area of contact points between aggregates increased which, in turn, increased the soil penetrometer resistance. In the cultivated soil, the significant increase in the volumetric water content which is related to the increase in bulk density might indicate that aggregate coalescence may occur at the expense of macro pores without necessarily increasing the volume of fine pores that hold water at 100 kPa suction. This result also suggests that in this soil, failure of soil aggregates by slaking and/or dispersion could be the major mechanism of aggregate coalescence. A similar mechanism may also occur in the virgin soil (Figure 8.3).

The similarity between the soil resistance at low and medium ESP in the virgin soil suggests the influence of organic matter in resisting structural changes. However at high ESP, the soil aggregates appear to start breaking down, presumably slaking and dispersion causing a slight but significant increase in soil strength. Clay dispersion will not occur, as long as soil aggregates stabilised by organic matter do not slake or breakdown (Murray and Quirk, 1991; Quirk, 2001). At high ESP organic matter appears to be ineffective in stabilising the soil structure. In soil high in exchangeable Na^+, organic bonds are generally fragile regardless of the linkage mechanisms (Rengasamy and Olsson, 1991). The dispersion of organic matter may be attributed to the transient organic bonds being broken (Emerson, 1983; Emerson and Chi, 1977; Nelson, 1997) during the wetting process.

Although the tensile strength at high ESP was relatively small, its creation indicates some coalescence had occurred possibly due to slaking or clay dispersion. Barzegar (1995) found that the tensile strengths of remoulded soils were related to both spontaneous and mechanically dispersible clay although the spontaneous dispersion showed a better correlation. In this experiment, it is difficult to make such links as conflicting results may appear as shown by Table 8.4. The mechanically dispersible clay of the cultivated Cornella and cultivated Rhynie soils appeared to be the only sensible trends.

Table 8.6. The turbidity (NTU) of 1 : 5 soil : water suspensions as affected by ESP

Soil	ESP					
	Spontaneous			Mechanical		
	low	medium	high	low	medium	high
Shepparton (c)	5	10	28	112	116	122
Shepparton (v)	2	2	9	66	64	73
Cornella (c)	18	29	30	90	116	154
Cornella (v)	4	20	141	78	110	167
Rhynie (c)	33	40	71	76	84	134
Wiesenboden(v)	14	15	33	91	88	90

8.4.2. Cornella clay

The effect of sodicity on aggregate coalescence in the cultivated Cornella soil was not as obvious as in the Shepparton soil when penetration resistance was used as an indicator. Various water contents and salinities may have confounded the results of penetration resistance and bulk density. An almost identical penetration resistance in soils with low and medium ESP may indicate that the effect of sodicity had been confounded by the significantly higher water content in the soil with medium ESP (see Figure 8.3). The significantly lower value of bulk density of soil with medium ESP indicated that more swelling had occurred in this soil and that in turn this may have prevented the expected increase in soil penetration resistance. At high ESP, a relatively high electrical conductivity (EC) might also reduce the effect of sodicity on soil structural changes. Table 8.2 shows that at high ESP the EC of the soil was 0.33 dS/m, 5 times higher than the EC of the soil with low ESP. It is well known that the degrading effect of sodicity on soil structure can be prevented by increasing the soil salinity (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Jayawardane, 1979; Crescimanno *et al.*, 1995; Quirk, 2001).

There was a consistent increase in tensile strength with increasing sodicity in the cultivated soil suggesting that more aggregates had coalesced with increasing sodicity. These increases appeared to be more related to the mechanically, than to the spontaneously dispersible clay (Table 8.6).

Although the penetration resistances of the virgin soil were much lower than the cultivated soil, the organic matter in this soil may not be able to prevent this soil from some structural decline due to increasing sodicity as shown by a significant increase in the soil penetration resistance. It might that the organic bonds in the virgin soil had been broken due to increasing sodicity. According to Quirk (2001), once the transient organic bond is broken, colloidal materials will be released. The dispersive effect of organic matter arises from the fact that the adsorption of organic matter occurs on the positive charges on inorganic colloids and disrupts the edge:face interactions that encourage flocculation (Frenkel *et al.*, 1992; Tarchizky *et al.*, 1993; Nelson, 1997).

8.4.3. Rhynie

The effect of sodicity on penetration resistance as a result of aggregate coalescence in the cultivated Rhynie soil appeared to be complicated by swelling and water content. Increasing sodicity from low to high ESP increased the swelling of the soils as evidenced by increasing soil volume with sodicity during wetting. This phenomenon was consistent with the bulk density which was significantly reduced with increasing sodicity indicating that the soil volume was increased at -100 kPa. Previous studies have shown that increasing sodicity causes soil aggregates to swell (McNeal and Coleman, 1966; Jayawardane, 1979). Furthermore, increasing sodicity appeared to have changed the soil water retention characteristics as shown by Fig. 8.3. The gravimetric water content increased from 0.28 to 0.44 g g^{-1} (an increase of almost 60%) as the ESP increased from low to high. Jayawardane and Beattie (1978) studied the effect of sodicity on the water retention characteristics of three soils. They found that the volumetric water content of the soils increased with the increase in sodicity.

The profile of soil penetration resistance of the cultivated Rhynie soil (Fig. 8.1) at a depth of less than 38.5 mm indicated that the swelling increase accompanied by increasing water content had weakened the intra-aggregate bonds causing the soil resistance to be reduced. However, at depths larger than 38.5, the penetrometer resistance of soil with medium ESP began to exceed that of soil having ESP 0.7. The increase in penetrometer resistance may be attributed to the presence of clay dispersion at this depth that overwhelmed the effect of water content on the soil resistance. The severity of clay dispersion at this depth appeared to cause a dramatic reduction in soil hydraulic conductivity and the upward water movement in this experiment. Table 8.5 shows that a very similar length of time was needed to wet a 35 mm thick soil core of low or medium ESP, but when the ESP was high the time needed increased dramatically by almost 7 times. The effect of sodicity on soil hydraulic conductivity has been studied widely (e.g. Rhoades and Ingvalson, 1969; McIntyre, 1979; Abu-sharar *et al.*, 1987; Shainberg *et al.*, 2001).

Table 8.7. The effect of sodicity on time needed to wet a 35 mm thick soil core

ESP	Time (minute)
0.7	2
4.8	3
10.9	20

In contrast to the penetration resistance data, the tensile strength of the cultivated Rhynie soil (Fig. 8.1) clearly showed that aggregate coalescence had increased as a result of increasing sodicity. A dramatic increase in the tensile strength of soil with high ESP indicated that clay dispersion might have greatly enhanced aggregate coalescence. The turbidity results (Table 8.6) appeared to confirm this phenomenon. Either the spontaneous or mechanically dispersible clay shows that the low and medium ESP have similar values but that it increase significantly at $P<0.05$ at the high ESP.

8.4.4. Wiesenboden

The trend in penetration resistance as affected by sodicity for this soil was very similar to that of cultivated Rhynie soil but smaller in magnitude possibly due to a higher organic matter content in this soil. The relatively similar bulk densities may indicate that either swelling is limited or swelling and aggregate collapse occur simultaneously in this soil. Water also appeared to confound the effect of sodicity on soil resistance as it tended to decrease up to a depth of 40 mm with increasing sodicity, although the resistance increased beyond this depth. As in other soils, the tensile strength increases in this soil may indicate evidence of aggregate coalescence. However, it is hard to relate this to the turbidity result (Table 8.6) as neither spontaneous nor mechanical dispersion show a similar trend to the tensile strength data.

8.4. Conclusions

Sodicity had different effects on aggregate coalescence at 100 kPa suction for different soils. Coarse-textured soil (Shepparton) showed consistent results between the penetrometer resistance and tensile strength in that they both tended to increase with increasing sodicity. For the clay soils such as Cornella, Rhynie and Wiesenboden, penetrometer resistance tended to decline as sodicity increased while the opposite was true for tensile strength.

The effect of sodicity on aggregate coalescence at 100 kPa suction in the coarse-textured soil might be enhanced by the occurrence of aggregate slaking and/or clay dispersion while in the clay this is obscured by the effect of water content and soil swelling. The effect of sodicity on aggregate coalescence could not be obviously observed by penetration resistance particularly in swelling soil, by contrast tensile strength increased with increasing ESP and this suggest that dispersion increased the strength in the point of contacts between natural aggregates which manifest in the form of aggregate coalescence.

Chapter 9 : The effect of aggregate coalescence on germination, emergence and early growth of tomato plants

9.1. Introduction

High soil resistance is a major problem in agricultural soil as a result of intensive tillage. However, it can also occur in soils that have no history of tillage and which have previously experienced no compaction, slaking or dispersion and yet plant roots appear to experience high resistance (Cannel, 1985). Cockcroft and Olsson (2000) suggested that aggregate coalescence might have occurred in these soils. These authors found that a coalesced orchard soil had penetration resistance of 2.3 MPa with bulk density of 1.4 g cm^{-3} while a nearby uncoalesced soil had penetration resistance of only 0.8 MPa with bulk density of 0.8 g cm^{-3}. A microscopic examination showed that the former soil had 100% of its aggregate coalesced compared to only 20% in the latter soil. However, the large difference in the bulk densities between these two soils might indicate that slaking or dispersion had occurred in the coalesced soil. It appeared that in the coalesced soil the orchard roots prefer to grow in previously existed biopores rather than through the bulk soil. This leads to questions on how annual crops respond to soil coalescence where their roots system need to establish themselves, rather than simply explore biopores previously created by perennial plant roots. Therefore, this experiment was designed to study the effect of an early stage of aggregate coalescence on the early growth of tomato. Coalesced and uncoalesced soils were deliberately created by different wetting processes. The objective of the study was to answer the question: Does an early stage of aggregate coalescence affect the germination, emergence and early growth of tomato?

9.2. Materials and methods

9.2.1. Soil

Two cultivated soils were used: Shepparton fine sandy loam and Cornella clay (Chapter 2). Aggregate fractions of 0.5 – 5 mm were used in this experiment. The aggregates were packed into cylindrical rings of 4.77 cm i.d. and 5 cm height (soil cores). The amounts of air dried soil used were 85 and

95 g for the Cornella and Shepparton soils, respectively; these resulted in dry bulk densities of ~1.1 and ~0.95 g cm^{-3} for the Cornella clay and Shepparton soils, respectively.

9.2.2. Planting and wetting procedure

Tomato (*Lycopersicum esculentum,* Mill*)*, cv. Gross Lisse was used as a test plant. Ten seeds per core were planted for germination and emergence experiments while three seeds were used in separate cores for the early growth experiment. The seeds were planted at 5 mm depth in the dry aggregates before imposing the initial wetting treatments.

Soils were initially wetted according to the following procedures aimed at simulating different field conditions (Table 9.1):

1. *Uncoalesced with slow irrigation (NC)*: In this treatment, the air-dried soil cores were wetted at a rate of 1 mm h^{-1}, controlled by a peristaltic pump, to achieve water contents at field capacity (10 kPa suction). The cores were then left at this suction for 24 h before being transferred to a pressure plate at 100 kPa suction. During plant growth, irrigation was conducted at a rate of 1 mm h^{-1}. This treatment was aimed at minimising slaking and coalescence.

2. *Coalesced with slow irrigation (Csl)*: The wetting process was the same as the uncoalesced treatment except that, after achieving water content at 10 kPa suction, the soil cores were brought to saturation (Chapter 2) for 24 h. Irrigation was the same as for the uncoalesced treatment. It was intended that the saturation period in this treatment would encourage the soil aggregates to coalesce, yet minimise slaking (and dispersion).

3. *Coalesced with rapid irrigation (Cfs)*: The wetting process was the same as the treatment 2 but with irrigation carried out by adding the amount of water needed at once.

Table 9.1. The treatments of cultivated Shepparton sandy loam and Cornella clay soil cores

Soil	Experiment	Treatment	Symbol	Min. suction during wetting (kPa)	Irrigation (mmh^{-1})
Shepparton	Germination	Uncoalesced	NC	10	n.a.*
		Coalesced	C	0	n.a.
	Emergence	Uncoalesced	NC	10	n.a.
		Coalesced	C	0	n.a.
	Early growth	Uncoalesced	NC	10	1
		Coalesced	Csl**	0	1
		Coalesced	Cfs#	0	Flooding
Cornella	Germination	Uncoalesced	NC	10	n.a
		Coalesced	C	0	n.a.
	Emergence	Uncoalesced	NC	10	n.a.
		Coalesced	C	0	n.a.
	Early growth	Uncoalesced	NC	10	1
		Coalesced	Csl	0	1
		Coalesced	Cfs	0	Flooding

* *Not applicable; there were only two treatments for germination and emergence experiments as the observation was conducted before irrigation was commenced.*

9.2.3. Irrigation procedure

During plant growth, soil water contents for each soil were allowed to decline each day until they reached values (by weight) corresponding to a suction of 125 kPa (Table 9.2). Water was then added (by weight) to reduce the suction to 75 kPa; this procedure was monitored and repeated throughout the plant-growth experiment.

Table 9.2. Water contents (g g^{-1}) of cultivated Shepparton and Cornella soil at different suctions

Soil	Suction (kPa)			
	10	75	100	125
Shepparton	0.173	0.113	0.109	0.102
Cornella	0.368	0.282	0.277	0.253

9.2.4. Germination and emergence experiments

Both the germination and emergence experiments were arranged in a completely randomised design with 4 replicates. Two treatments, uncoalesced and coalesced, were imposed for each soil (Table 9.1). Observations on germination and emergence were conducted before irrigation commenced, by removing the soil cores from the pressure plate extractor so for the germination experiment, the rate of germination and the length of radicles of the seeds that had germinated were obtained after 4 and 6 days using a digital calliper, using a total of 32 cores (2 soils x 2 treatments x 2 observations x 4 replicates). For the emergence experiment, only the time of emergence was observed, using 16 cores (2 soils x 2 treatments x 4 replicates).

9.2.5. Early growth experiment

The early growth experiments were arranged in a completely randomised design with 7 replicates. Three treatments were imposed on each soil (see Table 9.1) resulting in a total of 84 cores being used (2 soils x 3 treatments x 2 observations x 7 replicates). After 7 days, the extent of seedling emergence was evaluated by opening the pressure plates daily until there was sufficient emergence to proceed. After emergence, the soil cores were removed to a growth cabinet with a constant temperature of 20C and 14 h of light/d. Each soil core was covered with plastic beads to minimise evaporation losses. Plants were harvested at 6 and 10 d after emergence. Plant measurements conducted included:

- *Plant fresh weight, shoot fresh weight, root fresh weight*: Shoots were separated from roots and weighed. Roots were gently freed from soil using R.O. water, blotted dry and weighed.

- *Plant height, main root length, number of lateral roots, and lateral root length*: Whole washed plants were placed on moistened black paper on which the roots were spread out. Using a digital camera, images of the whole plants were taken. The length of individual roots and shoot height of the plants were determined using a Videopro 32 Colour Image Analysis system version 5 (Leading Edge Pty. Ltd., Australia).

Ten days after emergence, the shoots were removed leaving the roots in the soil cores. Prior to measuring penetrometer resistance and bulk density, the soil was irrigated to achieve a matric suction of 100 kPa. Penetrometer resistance measurements were conducted at three positions in every core with three replicates for each treatment (Chapter 2).

Analysis of variance was carried out using the *Genstat* 5 programme (Genstat, 1987). The least significant difference was calculated wherever the F-test was significant at $P<0.05$.

9.3. Results & Discussion

A major problem in the present experiment was that of high variability in the health of the tomato seeds resulting in high variability of seed germination and emergence.

9.3.1. Germination and emergence

There was a marked increase in the percentage of seed germination and the length of radicles as a result of different treatments (Figure 9.1). The uncoalesced treatment appeared to have a significantly higher percentage of germination, with an accompanying increase in radicle length. However, it seems unlikely that the soil treatment was the major factor that affected both the percentage of seed germination and the length of radicles. Penetration resistance values (Figure 9.4 and 9.5) between the treatments were similar up to 15 mm depth whereas the seeds were sowed at 5 mm depth. Therefore soil resistance appeared not to be a constraint for the seeds to germinate.

It is possible that the wetting process might have been a key factor. In the uncoalesced treatment, the soil was never saturated so that lack of oxygen was not a problem in this treatment. While in the coalesced treatment, the soil was left saturated for 24 h; this may have led the soil to be anaerobic for a certain period. Moisture levels surrounding the seed play an important role in controlling the ability of seeds to germinate (Özbingöl *et al.*, 1998). This is not only because the seeds need water to germinate but also oxygen for respiration. Al-Ani *et al.* (1985) found that the germination of various crop species decreased dramatically, as the partial pressure of oxygen declined in comparison to that of air, and that germination ceased when the oxygen pressure was very low. Tomato seed germination was greatly suppressed in soil containing less than 10 % oxygen and appeared to stop at oxygen concentration below 3 % (Özbingöl *et al.*, 1998). In pot experiments, Matev and Dulov (1972) found that the highest germination rate of tomato seeds occurred when the soil moisture water content was 70-80 % of field capacity. In the present work then, the temporary anaerobic condition in the coalesced treatment could have, therefore, delayed seed germination and emergence. The porosity of the Shepparton soil was 0.61 with volumetric water content of 0.44 at near saturation whereas the Cornella soil had porosity of 0.65 with volumetric water content of 0.52 at near saturation.

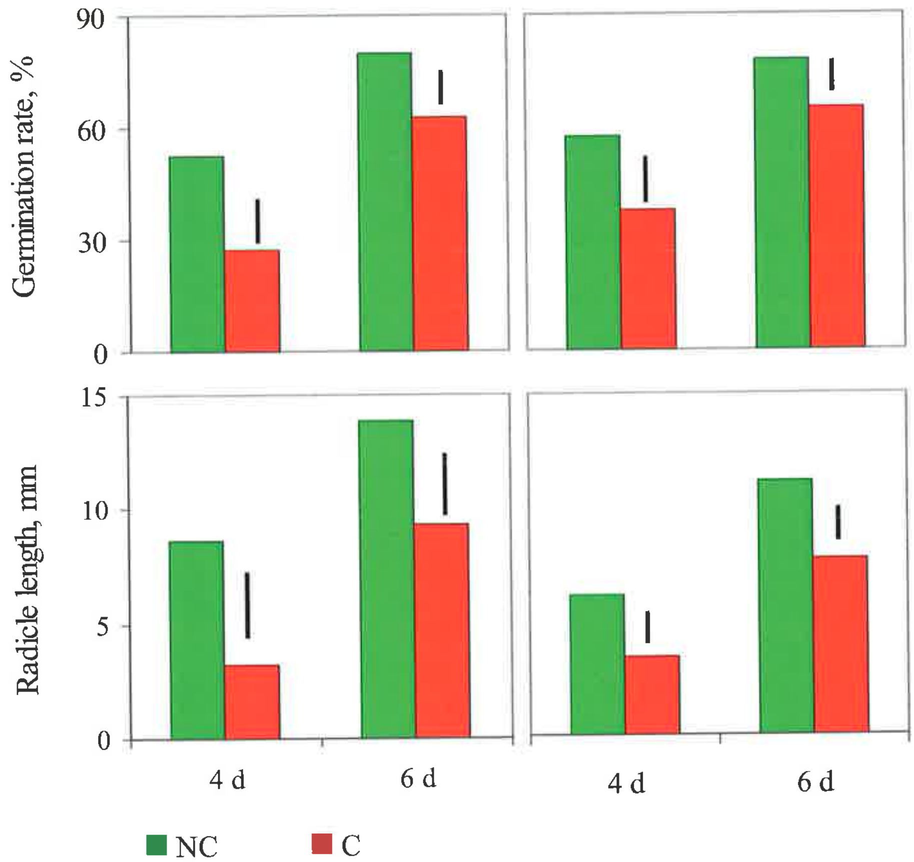

Figure 9.1. The effect of aggregate coalescence on germination rate and radicle length of tomato seeds at 4 and 6 d after sowing in Shepparton and Cornella soils
Vertical bars indicate least significant differences at P<0.05

The rate of tomato seedling emergence is presented in Figure 9.2. Emergence in the coalesced treatments for both soils was delayed for up to 2 d. This delay may be attributed to the delay of seed-germination due to lack of oxygen in the coalesced soil.

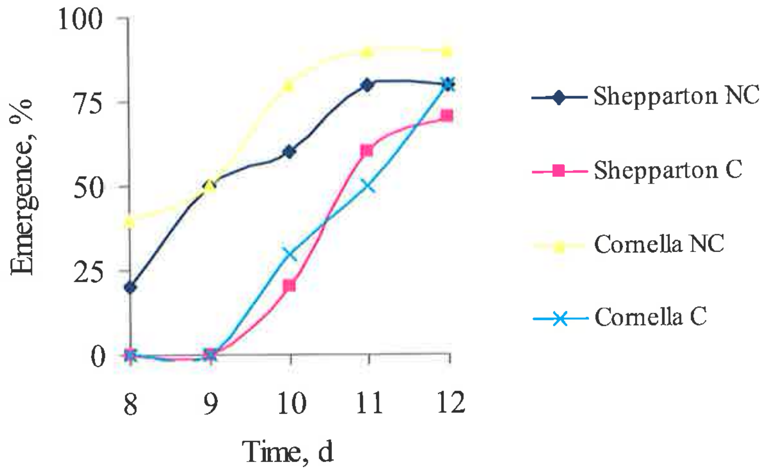

Figure 9.2. The rate of tomato seed emergence with different treatments at various times after sowing

9.3.2. Early growth

Cultivated Shepparton soil

There were no statistically significant differences ($P<0.05$) between treatments of the cultivated Shepparton soil for all plant parameters measured. However, the results of total root length were consistent in both harvests (6 d and 10 d) in that the uncoalesced treatment tended to have higher values than the coalesced treatments (Figure 9.3).

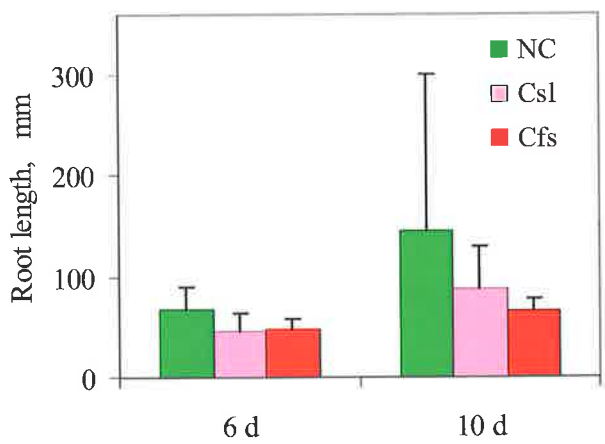

Figure 9.3. The effect of aggregate coalescence on the total length of tomato root at 6 and 10 days in Shepparton soil

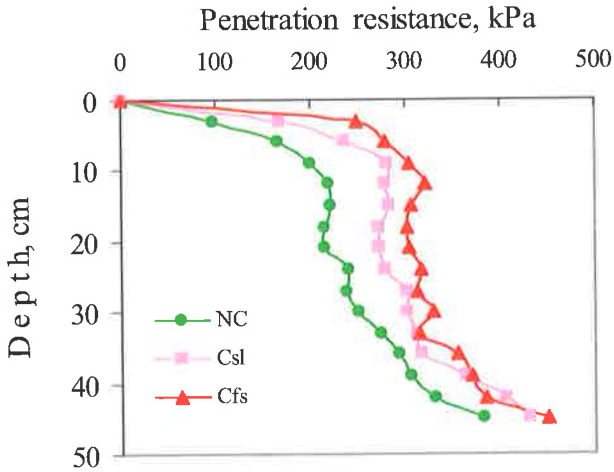

Figure 9.4. The effect of aggregate coalescence on penetration resistance at 100 kPa suction of cultivated Shepparton soil

The soil resistance of the Shepparton soil as a function of soil depth for different treatments is shown in Figure 9.4. Penetrometer resistance was measured 10 d after plant emergence. In general, the magnitude of the soil resistance appears to be below the critical point of 0.5 MPa (e.g. Bengough and Mullins, 1990) where roots begin to encounter difficulties. Moreover, the bulk densities of the coalesced and uncoalesced soils were very similar at 1.10 and 1.12 g cm^{-3}, respectively. However, the coalesced soil tended to have higher soil resistance than the uncoalesced soil although it was not statistically significant ($P<0.05$), this may have presented some problems for root growth of very young seedlings, especially for root attempting to explore the base of the soil cores.

In this experiment, the soil was exposed to only one cycle of wetting and draining and so any development of aggregate coalescence was at an early stage. The effects of on the early growth of tomato were apparent even though the results were not statistically significant at $P<0.05$. As suggested from the work in Chapter 4, a more advanced stage of aggregate coalescence after repeated wetting and draining may restrict plant root development more severely as the soil resistance rises beyond 0.5 MPa.

Cultivated Cornella clay

In the cultivated Cornella soil, the plant growth appeared to be normal until 7 days after emergence when the leaves started to change colour beginning at the tips. The plants eventually could not survive for the second harvest (*i.e.* 10 d after emergence). Visual observation of the plant leaves was consistent with the symptoms of plant death due to salinity in which death of a leaf occurred while the stem was still green (Wang, 1993). Later examination showed that the electrical conductivity of the soil (1:5) was found to be >0.4 dS/m which may be sufficient to cause problems particularly for a sensitive plant such as tomato. Due to this problem, observations were conducted only on the first harvest (6 days after emergence).

The effect of aggregate coalescence on penetration resistance was not statistically significant ($P<0.05$). It also appeared that aggregate coalescence in this soil had no significant effect on the plant and root parameters measured. Although the coalesced soil showed higher values of penetration resistance, there is no significant difference at $P<0.05$ and all soil penetrometer resistances (Figure 9.5) were below 0.5 MPa. At the same time the bulk densities ranged from only 0.906 to 0.926 g cm^{-3}.

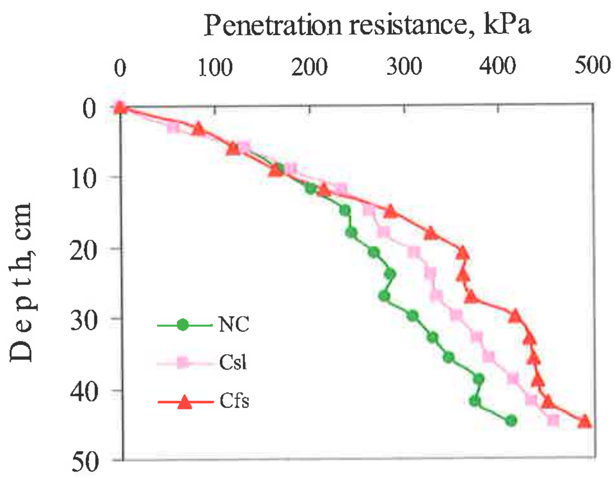

Figure 9.5. The effect of aggregate coalescence on soil resistance at 100 kPa suction of cultivated Cornella soil

Comparisons between plant growth in the Shepparton and Cornella soils

There were marked differences in the appearance of plants growing in the Shepparton and Cornella soils (Table 9.4).

Table 9.3. Shoot-root ratio, total root length and lateral root number, for plants growing in cores of cultivated Shepparton and Cornella soils at 6 d after emergence

Soil	Shoot root ratio	Total root length (mm)	Lateral root number
Shepparton	5 (0.5*)	54 (10)	10 (2)
Cornella	2 (0.3)	264 (11)	14 (1)

Data are presented as an average value of the three treatments (3 samples) from each soil
** Standard Deviation from three samples*

Total root length and number of lateral roots were much greater in the Cornella soil. Plants in the Shepparton soil had thicker stems and roots than in the Cornella soil suggesting that the root may have experienced greater soil resistance in the former soil than in the latter. Roots are known to thicken in soils of high strength (e.g. Shierlaw and Alston, 1984) in order to assist root penetration (Abdalla *et al.* 1969; Greacen *et al.* 1968). Materechera *et al.* (1991) used various crops to study the effect of mechanical constraints on root diameter. He found that regardless of the type of the crop, root diameter tended to increase with increasing soil strength. However, the soil resistance value alone cannot explain why roots in the Shepparton soil thickened, because the penetration resistances were similar for both soils (Figure 9.4 and 9.5). The marked differences may be associated with a different type of resistance that plant roots encounter in soils. The coarse texture of the Shepparton soil may present greater frictional resistance to root elongation than the Cornella soil. Penetrometers measure total soil resistance, which consists of physical resistance of soil to deformation plus frictional resistance at the penetrometer-soil interface (Bengough *et al.*, 1997). Kirby and Bengough (2002) stated that coarse-textured soils have a large proportion of frictional resistance causing the soil to have more axial and shear strength. The marked differences in the plant growth due to different types of resistance within the soil may also highlight the inadequacy of penetrometer readings in relation to root development.

9.4. Conclusions

The differences in the rate of seed germination and seedlings emergence (in both the cultivated Shepparton and Cornella soils) may have been affected by the lack of oxygen in the coalesced soils as a result of the initial soil wetting processes rather than the intended constraints (e.g. uncoalesced vs. coalesced treatments).

There were no significant differences in the early growth of tomato resulting from the treatments imposed. However, in the cultivated Shepparton soil, total root length was consistently higher in the uncoalesced treatment than in the coalesced treatment at both 6 and 10 days after emergence.

Soil penetration resistances and bulk densities in both the cultivated Shepparton and Cornella soils appeared not to be major constraints for plant growth, however, the fact that soil resistances approaches 0.5 MPa in soils of such low bulk density (<1 g cm^{-3}) is an indication that plant responses would likely to be greater as the soil gradually settles more realistic bulk densities in the field, say >1.3 g cm^{-3}.

The more pronounced effects of aggregate coalescence on the early growth of tomato in the Shepparton soil may be associated with the type of mechanical resistance the plant roots encountered within the soil cores.

Chapter 10 : General Discussion and Conclusions

10.1. General Discussion

Aggregate coalescence is thought to be a slow process progressing over a period of months and may occur in the absence of slaking and dispersion (Cockroft and Olsson, 2000; Lanyon *et al*, 1997). However, in the present study most experiments, except some described in Chapter 4, were carried out under conditions of relatively rapid wetting so that observation of the process of 'pure' aggregate coalescence without slaking and dispersion could not be achieved. The following discussion integrates the results from all experiments in this thesis and discusses them under the topics of 'pure' aggregate coalescence, aggregate coalescence and age hardening, aggregate coalescence and organic matter/PVA, aggregate coalescence and early tomato growth, and aggregate coalescence and its measurement.

'Pure' aggregate coalescence

'Pure' aggregate coalescence can be referred to as a condition where, in the absence of slaking and dispersion, aggregates are "welded" at their contact points without a significant increase in bulk density. Thus aggregate coalescence itself would seem to pose no risk to root growth as long as the strength at these points of contact does not increase beyond the ability of plant roots to cope. In the field, it may also not be possible to observe 'pure' aggregate coalescence because slaking and dispersion cannot be controlled. Although Cockroft and Olsson (2000) stated that aggregate coalescence occurs in the absence of slaking and dispersion, the data they presented show large differences in both bulk density and penetration resistance between coalesced and uncoalesced soil indicating that slaking or dispersion might have occurred causing the bulk density of coalesced soil to increase considerably. Furthermore, the organic matter content of the uncoalesced soil was much larger than the coalesced soil making it difficult to simply compare these as coalesced and uncoalesced versions of the same soil.

In the present study most of the experiments were conducted by more rapid wetting than might occur at depth in the field so that it was not possible to completely eliminate slaking and dispersion. The development of aggregate coalescence could not be observed independently from those processes. A good example of this can be observed in the sodicity experiment (Chapter 8). High ESP appeared to enhance slaking and dispersion in all soils and caused significant changes in either bulk density or water content. The responses of a coarse-textured soil (Shepparton) to these changes appeared to be different from the fine-textured soils. In the cultivated Shepparton soil, bulk density increased with increasing ESP but the gravimetric water contents remained the same resulting in a corresponding increase of soil penetration resistances. In the fine-textured soils, particularly the cultivated Rhynie soil, slaking and dispersion were complicated by this soil's swelling characteristic. Increasing ESP caused the swelling capacity of these soils to increase leading to increasing soil volume and thus lower bulk densities and higher gravimetric water contents. These contributed to a decrease in soil penetration resistance. In the aggregate size experiment (Chapter 6), apart from the slaking and dispersion interference in the aggregate coalescence process, the unavoidable difference of the initial bulk densities between various aggregate sizes made it impossible to separate the effects of aggregate coalescence on soil penetration resistance from those of changing bulk density.

However, in the matric suction experiment (Chapter 3), pure aggregate coalescence appeared to occur in a coarse-textured soil (Shepparton). Both the penetration resistances and tensile strengths of the cultivated Shepparton soil showed significantly larger values when the soil was wetted at near saturation compared to that wetted at 1 kPa suction. In this soil, the increase in penetrometer resistance occurred without significant changes in either bulk density or water content and suggests that the increase in soil strength was purely due to aggregate coalescence. In the fine-textured soils (Cornella and Wiesenboden), the significant changes in bulk density observed in this experiment have influenced the penetration resistance results.

The significant increase in penetration resistance without significant changes in the bulk densities of the Shepparton soil when wetting suction increased from 1 to 100 kPa (Chapter 3) may suggest that slaking and dispersion in soil could be controlled by very slow wetting and by this means pure aggregate coalescence may be observed as time progresses. However, it was found that slow wetting under suction was impractical to implement in the time available. At 1 kPa suction at least 12 and 48 hrs, respectively, were needed to completely wet the cultivated Shepparton and Cornella soil cores while the virgin Shepparton soil failed to fully wet even after one month (Chapter 3).

Aggregate coalescence and age hardening

The model presented by Ghezzehei and Or (2000) shows that during wetting, aggregate coalescence takes place as a result of plastic deformation at the points of aggregate contact and as coalescence proceeds, soil material flows radially from the contact points forming smoothed necks. It is not clear from the model how soil strength develops with time or during repeated wetting and draining cycles as Ghezzehei and Or (2000) only used soil strain to describe the changes. Age hardening may come into play as the process of aggregate coalescence develops resulting in soil strength increases. The strength increase may be due either to an increasing number of bonds or to the strengthening of previously formed bonds as time progresses (Dexter *et al.*, 1988). The most important processes in age hardening are associated with particle rearrangements (aggregate) and particle-particle bond formation.

In Chapter 4 the development of aggregate coalescence in the coarse-textured Shepparton fine sandy loam as measured by penetrometer resistance and tensile strength appeared to be more obvious than in the fine-textured Cornella clay. The coarse-textured soil showed consistent increases in both penetration resistance and tensile strength with repeated wetting and draining cycles. It is not clear which age hardening mechanism in this soil played the greatest role in increasing soil strength. The increases in bulk density with repeated wetting and draining cycles indicate that the number of bonds between aggregates increased with time. However, the existing bonds in this soil may have been reinforced as time progressed, possibly by cementation. Poorly ordered silica and aluminosilicates may be involved in such cementation processes (Chartres *et al.*, 1990; Bresson and Moran, 1995). The problem of aggregate coalescence in this coarse-textured soil and other soils can be exacerbated with soil depth as increasing overburden serves to drive aggregates together. This increase in aggregate coalescence with soil depth was shown by increases in both penetration resistance and tensile strength with increasing overburden (Chapter 5).

In the fine-textured soil as swelling and shrinkage occurred with repeated wetting and draining cycles, it is possible that the formation of new bonds and the loss of some formerly existing bonds may have occurred concurrently as indicated by fluctuations in penetration resistance (Chapter 4). While this may be generally true at any depth, overburdens at greater depths may restrict swelling and shrinkage during small fluctuations in water content. This restriction will enhance aggregate coalescence, as shown by increasing penetration resistance and tensile strength with overburden (Chapter 5). However, the increase in tensile strength with wetting and draining cycles might indicate that the net effect is that some bonds may have been strengthened as time progressed.

Aggregate coalescence and organic matter/PVA

Organic matter provided considerable resistance to aggregate coalescence and this was consistently observed throughout all the experiments regardless of soil type. In all experiments, virgin soils contained more organic matter and always displayed lower penetration resistance and tensile strength. Even under applied overburden pressures, virgin soils showed greater resistance to structural change (Chapter 5). The coarse particulate organic matter in the virgin soils kept soil structure more open (lower bulk density) than in the cultivated soils. A lower bulk density itself indicates that less points of contact between aggregates could be formed in virgin soils compared to cultivated soils. Furthermore, the particulate organic matter can also act as barriers between aggregates keeping them physically separated. The role of organic matter in aggregate stability is also well known allowing the soil to be able to resist more stresses compared with soils of low organic matter content (*e.g.* Stewart, 1998; Hartge, 1975). The hydrophobic nature of organic matter may also protect soil by reducing the rate of soil wetting. This may minimise the exchange of materials at points of contact between aggregates consequently reduce the extent to which aggregates coalesce. However, the role of organic matter in minimising aggregate coalescence may be diminished with time as its decomposition proceeds with repeated wetting and draining cycles (Chapter 4).

The use of PVA to minimise aggregate coalescence showed some trends although the results were not significant. PVA appeared to be more effective in reducing soil penetration resistance in the coarse-textured (cultivated Shepparton) than in the fine-textured soil (cultivated Cornella). However, the reduction of penetration resistances in the cultivated Shepparton soil was also accompanied by lower bulk densities suggesting that the effect of PVA was related more to the size distribution of soil aggregates than the process of aggregate coalescence itself.

Aggregate coalescence and early tomato growth

In the plant experiment (Chapter 9), although the results of root measurements did not show statistically significant differences between coalesced and uncoalesced soil ($P<0.05$), there were some trends in the Shepparton soil. The total root length in the coalesced Shepparton soil was consistently lower than in the uncoalesced soil at both 6 and 10 days suggesting that roots might encounter more mechanical impedance in coalesced soil, particularly near the bottom of the soil cores where penetration resistance approached 0.5 MPa

A very sharp contrast in plant growth was observed in the Shepparton (coarse-textured) and Cornella (fine-textured) soils. Plants in the former soil had thicker stems and roots, but the total length and number of roots were much greater in the latter soil, despite it having relatively higher penetration resistances. This suggests that plants in the Shepparton soil may suffer more from mechanical resistance than those in the Cornella soil. The different types of mechanical resistance encountered by roots in soil might be attributed to these differences in plant growth. It is probable that roots are more sensitive to frictional resistance, which is the major type of resistance in coarse-textured soil, than cohesive resistance. Therefore, aggregate coalescence in coarse-textured soils may have greater impact on plant growth than in fine-textured soils when both soils have similar penetration resistances.

Aggregate coalescence measurements

In the present study penetrometer resistance and tensile strength were used as the diagnostic tools for measuring aggregate coalescence. The accuracy of measuring aggregate coalescence with penetration resistance was confounded by variation in factors such as water content. It is well known that penetrometer resistance is greatly affected by soil water content (*e.g.* Smith *et al.*, 1997). In the present study, it was not possible to maintain identical water contents in a given soil where different treatments were imposed on it. The different treatments caused changes in the soil structure with consequent changes in the soil water retention characteristics. The obvious example of this problem was observed in the work discussed in Chapter 6 where significantly higher water contents were found in the finer aggregate fractions than in the coarser aggregate fractions of the Shepparton soil. For the fine-textured soils, a similar problem was also encountered in the work described in Chapter 8 where in a given soil, higher ESP generally caused water contents to be higher. The other confounding factor in penetration resistance was bulk density. The relatively rapid wetting imposed in most experiments meant that slaking and dispersion could not be eliminated and this caused unavoidable changes in bulk density. In Chapter 4, repeated wetting and draining cycles caused the bulk densities of both the coarse- and fine-textured soils to change significantly. The effect of aggregate size on aggregate coalescence (Chapter 6) also encountered difficulties in controlling bulk density changes. Unfortunately it is not possible to simply correct observations for these changes as there is probably no unique relationship between soil strength and either bulk density or water content even for a given soil. Any single value of bulk density or of water content may correspond to a number of structural states depending on the history of the soil.

An index of aggregate coalescence based on changes in penetration resistance and bulk density (Chapter 4) as proposed by Grant *et al.* (2001) showed a relatively constant value with time (wetting and draining cycles) and this may partly confirm the confounding effect of water content on penetrometer measurement. Based on tensile strength changes, the index showed increases as time progressed and this could indicate that increasing soil strength was due to the development of aggregate coalescence. This result may suggest that tensile strength may be used as a more reliable tool for aggregate coalescence measurement. However, the relevance of tensile strength measurement in relation to root growth appeared to be small. Therefore, it is important to include plant growth itself as another tool for aggregate coalescence diagnosis. In the plant experiment (Chapter 9), although the results of root measurements did not show significant differences between coalesced and uncoalesced soil, the trend in the Shepparton soil, however, appeared to show an effect.

10.2. General Conclusions

In the present study, it was not possible to observe the development of pure aggregate coalescence in conditions where slaking and dispersion were absent because of the methods used for soil wetting. The use of relatively rapid wetting as the major method of soil wetting in most of the experiments caused slaking and dispersion to contribute to structural changes. The changes in soil structure due to slaking and dispersion processes lead to measurements of aggregate coalescence using penetrometer resistance being confounded by changes in water content and bulk density. The water content factor can at least be avoided by using tensile strength as a tool to measure aggregate coalescence on air-dried materials. From the present study, it appeared that aggregate coalescence can be minimised by either maintaining high organic matter content in soil or wetting the soil very slow.

Further research in aggregate coalescence should focus more on integrating overburden and repeated wetting/draining cycles over time as these two factors appeared to be the most important factors affecting aggregate coalescence. There are several things that may need to be taken into account in conducting such research including the wetting method, the dimension of soil cores and aggregate sizes used. As slow wetting has proven to take a long period of time for soil to be wetted, fast wetting from the base of soil cores may still be applicable but larger soil cores than the ones that used in the present experiments (*e.g.* 15 cm diameter and 50 cm high) need to be employed. In this way the bottom part of the soil cores in which slaking and dispersion occur can be sacrificed leaving the rest for observations. Another method of wetting is a top-down wetting using a device such as a peristaltic pump. In this way gravity can also assist downward water movement, and to prevent the topsoil from damage due to water drop impact, a filter paper can be used to cover it. Larger soil cores can also offer the advantage in observing how overburden affects aggregate coalescence by allowing the soil core to be divided into different sections making it possible to investigate them separately according to soil depth. The use of uniform aggregate size (*e.g.* 2 mm) is also important to be employed as this could reduce the possibility of various bulk densities at the initial stage of an experiment.

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