CHAPTER 7

EFFECTS OF THE PHYSICAL PROPERTIES OF TAILINGS ON PLANT GROWTH

7.1 INTRODUCTION

The growth of plants is influenced by external climatic factors, nutritional status of the soil and soil physical properties. The results of the chemical analyses (Tables 5.2, 5.3 and 5.5) and the pot trials (Chapter 6) did not reveal any definite chemical problems in the tailings that would adversley affect plant growth. The reduced growth and root morphologies achieved in the pot trials may, however, be due to adverse physical properties of the tailings.

In view of the results achieved in the pot trials further studies were undertaken to investigate the effect of the physical properties of the tailings with particular reference to aeration, mechanical resistance, bulk density and their relation to matric potential. In the main literature review, given in Chapter 2, the physical properties of tailings were treated briefly. Because of the significance of the Hillgrove tailings for plant growth it was considered desirable to review further, the physical factors affecting root growth.

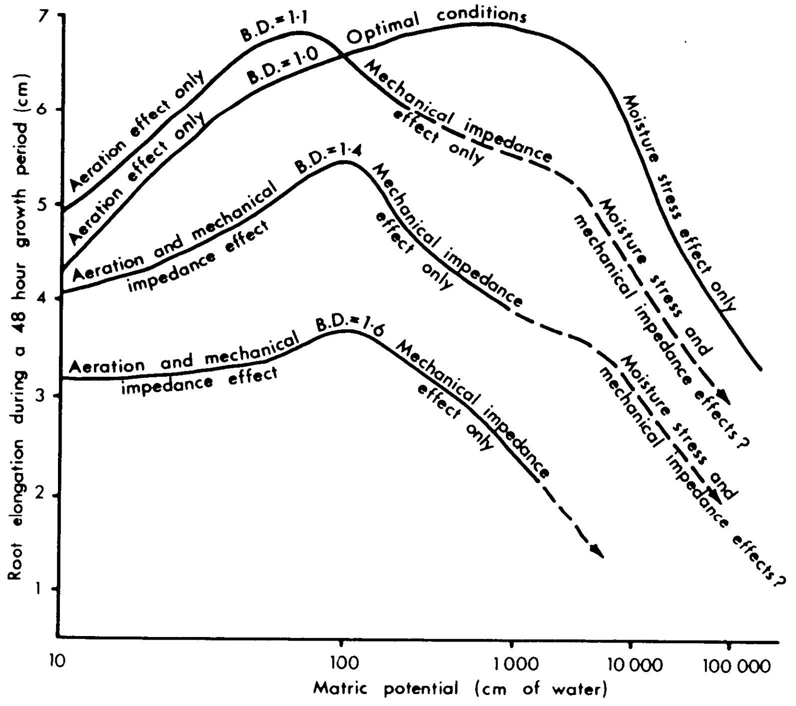
7.2 EFFECTS OF AERATION, MECHANICAL RESISTANCE AND BULK DENSITY ON PLANT GROWTH

7.2.1 Introduction

The relative importance of mechanical impedance, aeration and availability of soil water is uncertain because of their strong interrelationships. Thus, changes in bulk density and water content lead to changes in aeration and mechanical resistance (Taylor and Ratliff, 1969a; Eavis, 1972). Decreasing soil water potential causes soil strength to increase giving rise to increased mechanical impedance for roots (Russell, 1977).

Eavis (1972) conducted experiments to obtain quantitative data for the separate effects of aeration, mechanical resistance and moisture stress on pea (*Pisum sativum L.*) seedlings in a sandy loam soil packed at different water potentials and bulk densities (Figure 7.1).

FIGURE 7·1 : Summary of Role of Mechanical Impedance, Aeration and Moisture Stress on Pea Seedling Root Elongation in a sandy loam held at Different Matric Potentials and Bulk Densities. (After: Eavis, 1972.)



Aeration was limiting at high water potentials but mechanical resistance was the over-riding factor controlling root growth in this soil type through most of the available water range. An aeration effect was found in soils having less than 30, 22 and 11% gas filled pore space at bulk densities of 1.1, 1.4 and 1.6 g cm^{-1}.

7.2.1.1 Aeration

Soil aeration is that part of the gaseous cycle involving the interchange of CO_2 and O_2 between soil organisms, soil and the aerial atmosphere (Grable, 1966). For optimum growth, plants must be supplied with both air and water in the root zone. Therefore a compromise must be reached between soil air and moisture contents, which will differ according to soil type, structure and plant species (Currie, 1962; Grable, 1966).

The minimum gas filled pore space necessary for optimum plant growth depends on the size of the gas filled pores (Bunt, 1961), and soil texture (Hanks and Thorp, 1956). The minimum oxygen content depends on the amount of soil water (Gingrich and Russell, 1957), bulk density (Tackett and Pearson, 1964a, b), and temperature (Cannon, 1925). Greenwood (1970) suggests that, as a general rule, oxygen diffusion rates will not limit growth in soils with more than 12% gas filled pore space. Wesseling and van Wijk (1957) concluded that 10% by volume of air filled pores is the lowest value at which air can be exchanged. Tackett and Pearson (1964a, b) found that root penetration was decreased with reductions in O_2 concentration between 10 and 1.2%, while in high density soil, O_2 concentration was relatively unimportant in controlling root growth.

7.2.1.2 Bulk Density

Bulk density has been widely used as an indicator of resistance to root growth. (Veihmeyer and Henderickson, 1948; Bertrand and Kohnke, 1957; Borden, 1961; Craze, 1977). However, some workers have pointed to its limitations. For example, Zimmerman and Kardos (1961) found that bulk densities and root penetration were only positively correlated in about half of their studies on a series of soils. Similarly, Veihmeyer and Hendrickson (1948) found that bulk density was not the only limiting factor to root growth during studies in which they grew sunflowers in a gravelly loam soil to a depth where the density was 1.8 g cm^{-3}. They concluded that the size of the pores was a significant factor in conjunction with bulk density.

Compaction of soil not only decreases the total pore space but also changes the pore size distribution (Rimmer, 1980). In general, with increasing compaction (density) there will be a reduction in the number of large pores. The ease with which particles will pack is not well understood. However, it is likely to depend not only on particle size distribution but also on particle shape and interparticle forces (Mullins and Panayiotopoulos, 1980).

7.2.1.3 Mechanical Resistance

Soil strength can be defined as the mechanical resistance, which is determined in a complex way by the strength and compressibility of soil (Farrell and Greacen, 1966). Mechanical resistance as measured by a penetrometer generally rises with increasing bulk density and declining water content (Taylor and Gardner, 1963; Barley *et al.*, 1965; Taylor *et al.*,1966; Eavis, 1972). Soil strength changes not only with bulk density and water content, but also with types and amounts of cations, the number of particle to particle contacts, the type of clay material and the amount and type of organic materials (Taylor, 1974).

The effects of mechanical resistance on root extension appears to be greater when the supply of oxygen is limited (Gill and Miller, 1956; Barley, 1962; Russell, 1977). Hopkins and Patrick (1960) state that the effect of mechanical resistance probably over-rides any aeration effect in compacted soils. The results of studies on cotton root penetration indicated that little or no penetration occurred with a cone penetrometer resistance of 2,138 kPa and an O_2 content of <10% (Taylor and Gardner, 1963). Greacen and Sands (1980) state that a penetrometer resistance of 2,500 kPa is often regarded as being critical for the growth of plant roots.

Pfeffer (1893) found while studying root and shoot growth in a gypsum block that the roots could exert a force corresponding to a pressure of 500 to 1,000 kPa, while Muller (1872) found that a mechanical pressure of 1,400 kPa was need to prevent the growth of pith isolated from the stem of the sunflower (*Heliomthus annuus L.*) Wiersum (1957) has noted that root tips of germinating seeds of such species as field bean (*Vicia faba*) and corn (*Zea mays*) can exert pressures of 500 to 2,400 kPa.

Roots in a rigid medium cannot enter pores smaller than their own diameter even if apices gain entry (Wiersum, 1957; Russell and Goss, 1974). Batey (1975) and Greenland (1978) concluded that roots will be confined largely to continuous aggregates, pores and fissures. However, Barley *et al.* (1965) state that roots can penetrate clods and horizons that lack wide pores by deforming the soil. Soils resist this deformation, and growth may be prevented if their strength is sufficiently high.

The pot trials indicated that root growth was very restricted. The strength characteristics of the tailings and the inter-relationship with aeration and water potential were therefore investigated further.

7.2.1 Materials and Methods

Dry samples of 100% sands and 100% slimes were collected and prepared as described in chapter 5.2 and placed in 38 mm conduit rings and wetted up to 2 cm water tension on a tension table. Each was replicated three times.

Samples were placed on suction plates for the determination of moisture content at 10 cm, 50 cm, 100 cm and 200 cm soil moisture tensions. A ceramic plate was used to determine the 500 cm, 1 bar and 3 bar tensions. Samples were allowed to equilibrate for 10 days, after which penetrometer readings and moisture contents were determined.

A constant depth penetrometer (Plate 7.1) similar to that described by Eavis (1972) was used to measure the mechanical resistance of the samples. A stainless steel probe 1.6 mm in diameter with a 60^{o} point, was slowly driven by a screw mechanism to a depth of 6 mm into prepared cores placed on a top pan balance.

The increase in weight on insertion of the probe was recorded after equilibrium had been reached, usually after one to five minutes. Three readings were taken per sample core. The average reading was converted to point pressure in kg cm^{-2} (1 kg cm^{-2} = 100 kPa or 1 bar) by dividing it by the cross sectional area of the probe. Point pressure in kPa is used as a relative index of mechanical resistance.

Mean total porosity of each core was calculated using a particle density of 2.75 g cm^{-3} for the sands and 2.70 g cm^{-3} for the slimes (Section 5.4.2). Bulk densities were determined at each moisture tension by calculating the mass per unit volume of each core after samples were oven dried. The short comings of this method of determining bulk density are discussed in Section 7.2.3.

7.2.2 Results

The mean data for air filled porosity and mechanical resistance at varying matric suctions for the sands and slimes tailings fractions are displayed in Figures 7.2 and 7.3 respectively,

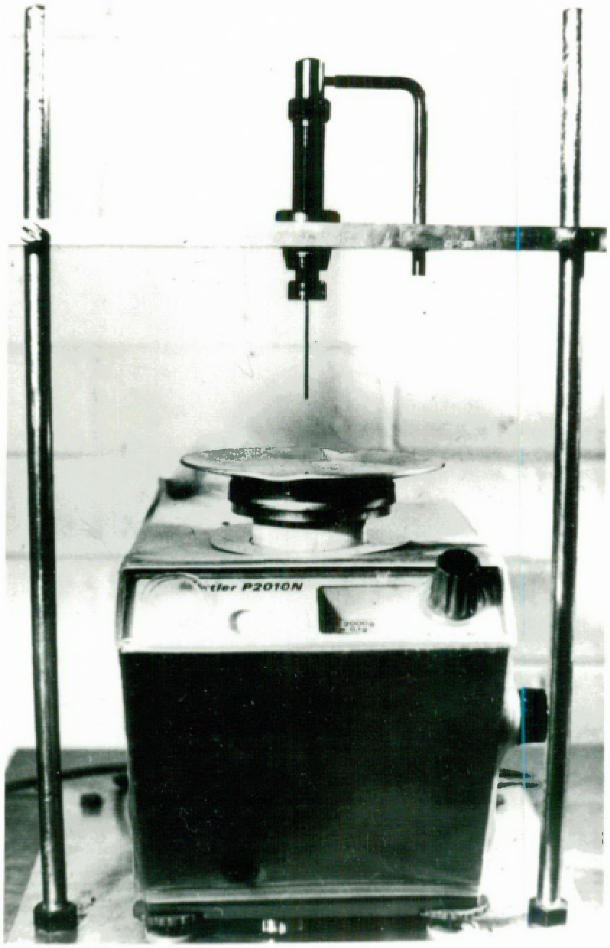


Plate 7.1: Penetrometer and balance used to determine the mechanical resistance of tailings mixtures.

Figure 7·2

Variation in Airfilled Porosity and Mechanical Resistance with Matric Suction in the Sands Tailings Fraction.

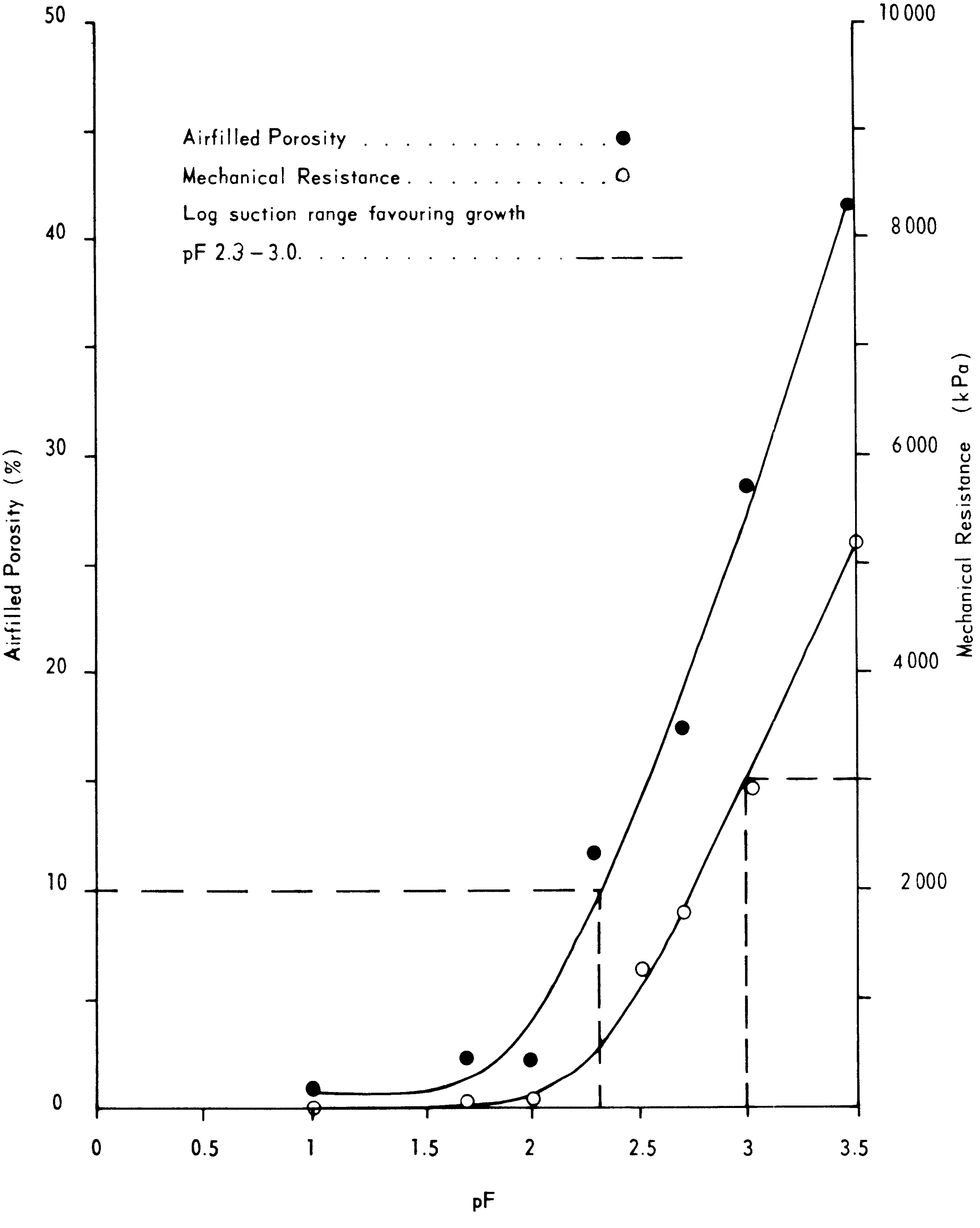
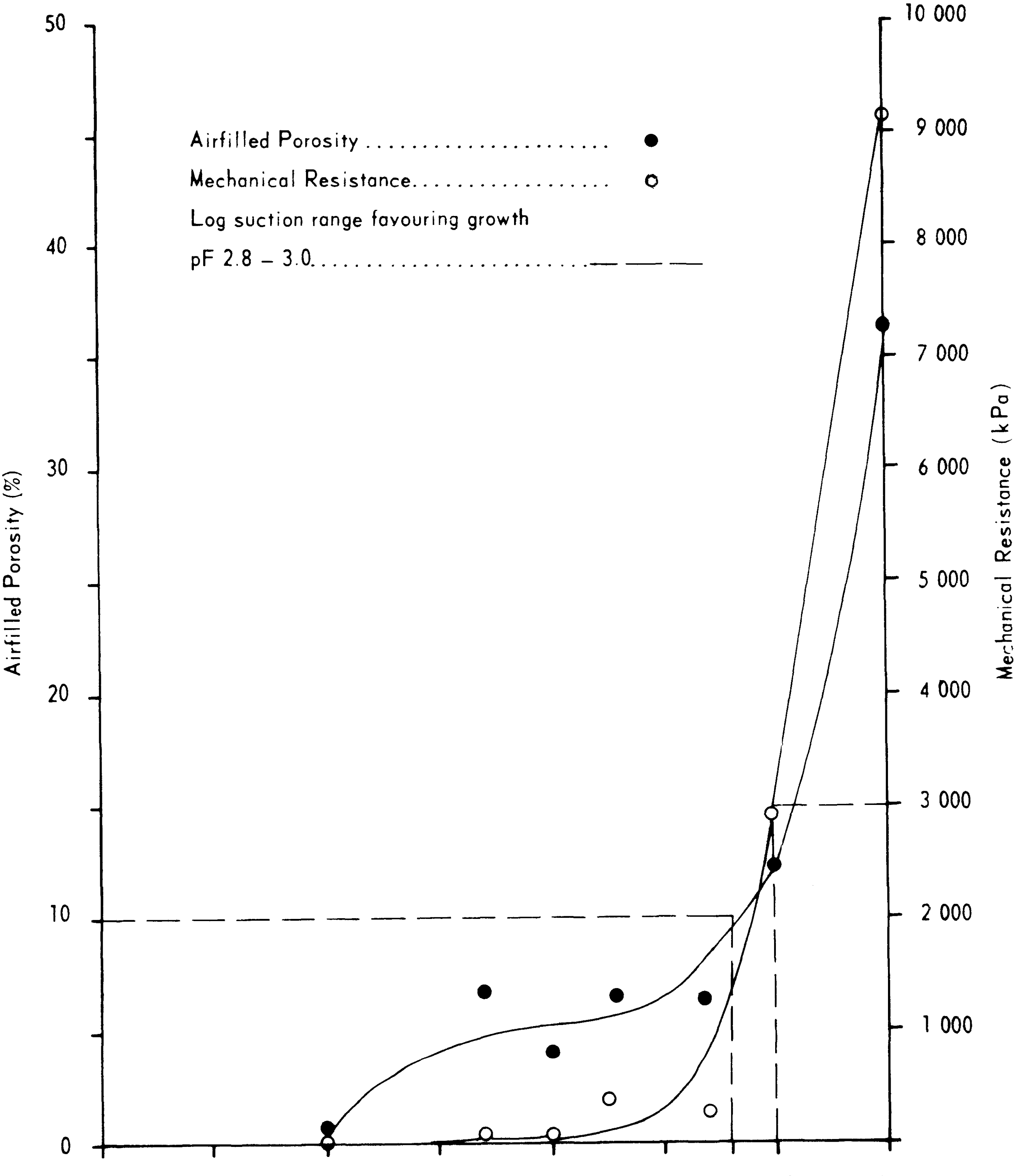


Figure 7·3 :

Variation in Airfilled Porosity and Mechanical Resistance with matric suction in the Slimes Tailings Fraction.



In both fractions there was a rise in mechanical resistance with increased matric suction, with the slimes fraction recording a maximum of 9,120 kPa at pF 3.5. This corresponded to a resistance of 5,140 kPa for the sands fraction at the same matric suction. At pF 1.0 no resistance was recorded in either the sands or the slimes samples. There was a sharper increase in mechanical resistance in the slimes fraction at the higher matric suction (>pF 2.7) than in the sands fraction. Air filled pore space increased with increasing matric suction, reaching a maximum of 41.4% at pF 3.5 for the sands fraction, and 36.1% for the slimes.

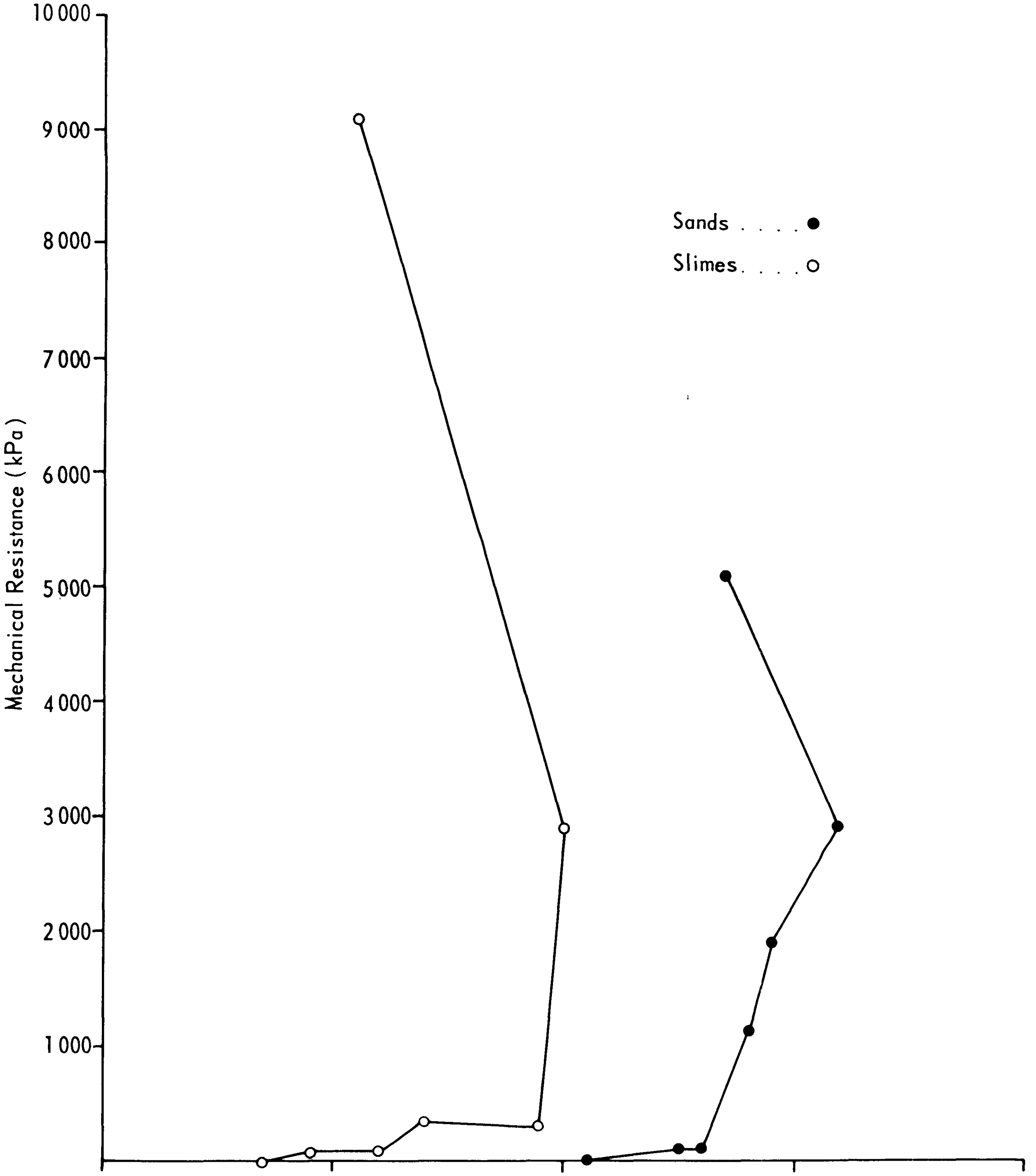
Figure 7.4 shows mean bulk density plotted against mean mechanical resistance. The trend was for an increase in bulk density with increasing mechanical resistance, up to approximately 3,000 kPa. Bulk density then declined with increasing mechanical resistance in both tailings fractions.

7.2.3 Discussion

The limitations of the tailings as a medium for plant growth are highlighted by the results illustrated in Figures 7.2, 7.3 and 7.4. The interrelationship between mechanical resistance, matric suction and airfilled pore space is in general agreement with the findings of Taylor and Gardner (1963), Eavis (1972), and Mirreh and Ketcheson (1972). All found that mechanical resistance rises with increasing bulk density and decreasing water potential.

Figure 4 shows that whilst there was a general trend for mechanical resistance to increase with increasing bulk density; the bulk density values obtained at pF 3.5 showed a noticeable decrease whilst mechanical resistance continued to increase. This discrepancy is probably due to the method of bulk density determination. At the higher matric suction, more water was removed from the pores and the material may have shrunk. By determining the bulk density on the known volume of the conduit a false reading was obtained. The variability in the bulk densities at the other matric suctions may also be due to this experimental error. The error in measurement of bulk density by this method is indicated by the values obtained for the saturated samples which were allowed to air dry and

FIGURE 7·4: Relationship between Bulk Density and Mechanical Resistance in the Sands and Slimes Tailings Fractions.



coated with Saran resin (see Section 5.4.2). The mean values for the sands and slimes were 1.58 g cm^{-3} and 1.53 g cm^{-3} respectively. If it is assumed that the dried samples were at a pF of 4.5, then these values are appreciably higher than those obtained at pF 3.5 by the present experiments (Figure 7.4). This error in bulk density determination will affect the determination of air filled porosity. However, this would only be at the higher end of the scale where mechanical resistance and not aeration has been shown to be the most significant factor affecting root growth (Figures 7.2 and 7.3).

Bulk density is known to affect root growth (Pfeffer, 1893; Carlson, 1925; Gupta, 1933; Browning and Sudds, 1942; Forristal and Gessel, 1955; Fehrenbacher and Rust, 1956; Wiersma, 1959; Schuurman, 1965). Critical soil densities for root growth have been noted by several workers (Table 7.1).

Compaction leads to an overall reduction in volume. In an unsaturated granular material such as the sands fraction, compaction will be achieved by the rearrangement of the angular soil particles by rolling and sliding, while in a fine grained material such as the slimes which is dominated by clay and silt size particles, the volume change results from a combination of particle reorientation and the displacement of liquid from between particles (Rimmer, 1980). This would apply to the tailings fractions.

The importance of the affect of particle size distribution on bulk density has been shown by Mullins and Panayiotopoulos (1980) by mixing coarse and fine sand together in the ratio of 3.5 to 1. They achieved a 5.2 and 29.8% increase in bulk density over the original values for the coarse and fine sand respectively.

The relative importance of mechanical impedance, aeration and availability of soil water is uncertain because of their strong inter-relationship. However, changes in bulk density or water content lead to changes in aeration and mechanical resistance (Taylor and Ratliff, 1969a, b; Eavis, 1972). Decreasing soil water potential causes soil strength to increase giving rise to increased mechanical impedance for roots (Russell, 1977).

Changes in matric suction above pF 2.3 for the sands and pF 2.7 for the slimes produced significant increases in soil strength, as measured by penetrometer resistance (Figures 7.2 and 7.3). The rise in soil strength at these matric suctions is probably due to the interaction of particle shape, particle size distribution, pore size and matric suction. The sharp increase in soil strength for the slimes at pF 2.7 as compared to

Table 7.1 Critical Bulk Density Values Recorded by Several Workers

Workers	Year	Critical Density Sand	 Loam
Veihmeyer and Henderickson	1948	1.75	1.48-1.63
Forristal and Gessel	1955		1.3 -1.8
Fehrenbacher and Rust	1956		>1.7
Bertrand and Kohnke	1957		>1.5
de Roo	1957		>1.67
Wiersema	1958	1.70 = por. vol. 32% at 2% humus	por. vol. 35%
Borden	1961		1.4-1.5
de Roo	1961		1.6
Rosenberg and Willits	1962	>1.60	>1.64
Craze	1977		>1.57

the more gradual increase from pF 2.3 for the sands is attributed to the different moisture release characteristics of the materials and the relationship between matric suction shear strength and effective stress for the two materials. The theories of effective stress and its relationship with matric suction and soil strength is discussed by Aitchison (1961), Towner and Childs (1972) and Mullins and Panayiotopoulos (1983).

Microscopic examination of the sands and slimes tailings fractions has shown the particles to be angular and subangular and ranging in sphericity from spherical to subspherical. This angular type of particle shape arises from the crushing of the mined rock. The tendency for such particles to pack closely is strong, and this arrangement of particles with increasing matric suction leads to a reduction in pore size and an increase in bulk density and soil strength.

The resistance of soil to deformation is made up of two forces. Firstly, frictional forces at the interparticle contact areas that resist the sliding of particles and secondly, cohesion forces which hold particles together (Terzaghi and Peck, 1948; Capper and Cassie, 1963; Yong and Warkentin, 1966). The magnitude of the frictional forces is governed by the frictional properties of the soil material and the extent and condition of interparticle areas of contact, while particle cohesion is governed by the cementing materials present, such as organic matter derivitives, and the strength of the moisture bonds holding particles together (Haines, 1927; Aitchison, 1961). The contribution of these latter bonds to particle cohesion is a function of soil moisture tension, pore size distribution and the degree to which various sized pores are drained (Capper and Cassie, 1963; Williams and Shaykewich, 1970).

Mullins and Panayiotopoulos (1983) conducted experiments with mixtures of sand and kaolin and compared the Coulomb-Mohr theory of soil strength combined with the concept of effective stress to the behaviour of the samples under unconfined compression and indirect tensile strength tests. They found strength was well correlated with water content and pore water tension. In particular, there was a sharp increase in strength between tensions of 10 k Nm^{-2} and 1 M Nm^{-2}. This increase was found to occur for a comparatively small reduction in water content. This sharp increase was similar to the one obtained in the slimes fraction (Figure 7.3).

Eavis and Payne (1969) attempted to compare the axial pressures experienced by roots when penetrating soil with those measured by penetrometers of comparable size. In a sandy loam soil, a small pore water suction (2.0 kPa) reduced root extension to 50% of the maximum, but this occurred only in compacted soil in which penetrometer resistance was about 3,400 kPa and root growth pressure was 380 kPa. This soil is similar in texture to that of the sands fraction depicted in figure 7.2. In other soil types much higher water tensions are necessary to give resistances that significantly effect root extension (eg. Taylor and Gardner, 1963; Gooderham and Fisher, 1975).

Penetrometers are generally used to provide an index of mechanical resistance. Because of variations in probe design, heterogeneity of resistance in field soils, and differences between roots and metal probes in their mode of penetration, penetrometer resistance lacks general utility as a predictor of root growth (Greacen *et al.*, 1969). In addition, both bulk density and penetrometer resistance provides no direct information on the continuity of pores or planes of weakness in the soil.

Despite these limitations penetrometer data has been found to correlate well with root extension provided that the measuring technique is constant. The results of the penetrometer data in this study are in agreement with the findings of Taylor and Gardner (1963), Eavis (1972) and Mirreh and Ketcheson (1972) who found that penetrometers are a useful index of resistance in reasonably homogeneous field soils and in experiments with remoulded soils. However, even if penetrometers are made to resemble roots in shape, there are three basic characteristics of the growing root which cannot be simulated; the considerable capacity of its apex for deformation in response to external pressure, the ability of the root to curve around obstacles and the possible lubricating effect of the mucigel sheath which is developed on the root cap (Russell and Goss, 1974).

Calculations of root growth pressure from penetrometer resistance suggests that the maximum pressures exerted by roots for enlargement of the growth cavity are in the range 500-1,000 kPa (Greacen *et al.*, 1969; Greacen and Oh, 1972). Greacen *et al.* (1969) state that for penetrometers with blunt points (>30°) deformation is by radial enlargement of a spherical cavity while for acute points (<5°) it is by radial enlargement of a cylindrical cavity. The point of the penetrometer used in this study was at 60° and, as such, deformation of soil would be expected to be by radial enlargement. However, this does not correspond to the method of soil deformation by root, as Greacen *et al.* (1969) states that roots penetrate the soil by radial enlargement of a cylindrical cavity.

Russell and Goss (1974) state that the comparison of penetrometer resistance to the pressures exerted by root tips is doubtful because root hairs within a few millimetres of root apices anchor them to the soil when subjected to a mechanical restraint. They also state that the different effects that root apices and the tips of some penetrometers have in deforming the soil as previously described is a further reason why penetrometers should be regarded as comparative and not absolute guides to forces roots experience in penetrating soils. It is not necessary, however, to know the exact relationship between penetrometer resistance and the pressure applied by a root provided the penetrometer is used only as a comparative index of resistance (Cornish, 1979).

The published literature cites various penetrometer resistance values as limiting to plant growth. This is due to the variation in soil properties and shape and size of penetrometers. Resistance values that limit growth have been reported within the range of 5,000 to 8,000 kPa for peas (Greacen *et al.*, 1969). In a study of compaction of sandy soils in a Radiata pine, (*Pinus radiata*) forest with a penetrometer Sands *et al.* (1979) concluded that root penetration was severely restricted above a critical penetration resistance of about 3,000 kPa. These studies were carried out with a probe length of 80 cm and a core basal area of 1 cm^2 and a semi angle of 30°. Pfeffer (1893) found that root elongation was delayed several hours when roots of (*Vicia faba*) were grown in media offering a resistance of 300 kPa to a probe of 1 mm radius. Elongation was prevented when the probe resistance exceeded 1,200 kPa.

Taylor and Gardner (1963) in studies of taproots of seedlings found that the percentage of taproots penetrating through cores of Amarillo fine sandy loam decreased progressively as penetrometer soil strength increased, Taylor and Burnett (1964) found that a penetrometer resistance of 2,500 kPa at field capacity in Amarillo fine sandy loam was sufficient to prevent root extension.

In the majority of studies cited a penetrometer resistance of about 3,000 kPa was sufficient to prevent or markedly reduce root elongation. The maximum resistance recorded in the sands fraction was 5,140 kPa while in the slimes fraction this increased to 9,120 kPa. These resistance figures are well in excess of 3,000 kPa and as such it could be assumed that root growth would be severely restricted at such high levels. A penetrometer resistance of 3,000 kPa was achieved at pF 3.0 in both the sands and slimes fractions (Figures 7.2 and 7.3). At pF 2.4 in the slimes, the value taken for field capacity, the mechanical resistance was only 300 kPa. At this matric suction mechanical resistance would not be expected to be a problem (Greacen *et al.*, 1968). However, in the sands the mechanical resistance at this pF was 1,200 kPa. Using the resistance value of 2,500 kPa recorded at pF 2.4 by Taylor and Burnett (1963) as a guide, some limitation to root growth could be expected in the sands fraction at field capacity.

At lower matric suction airfilled porosity and not mechanical resistance would appear to be the main limiting factor for root growth (Figure 7.2 and 7.3). The factors affecting the minimum gas filled pore space and minimum oxygen content necessary for optimum growth have been previously discussed, namely the size of the pores, soil texture, amount of soil, water and bulk density. Whilst there is conjecture about the minimum gas filled pore space required for growth, a figure of 10% as stated by Wesseling and van Wijk (1957) would appear to be a suitable figure based on available literature. This figure would also appear to correlate reasonably well with the optimum air filled porosites cited by Baver (1956) for wheat and oats of 10 to 15%.

Taking 10% as the minimum, aeration would be limiting to growth in the slimes fraction at matric suctions up to pF 2.8 (Figure 7.3), while in the sands fraction at matric suctions up to pF 2.3 (Figure 7.2). In the slimes fraction the log suction range favouring growth is very small 2.8-3.0. Below pF 2.8 aeration would be limiting whilst above pF 3.0 mechanical resistance would restrict growth. In the sands fraction the log suction range favouring growth is pF 2.3-3.0 (Figure 7.2). Aeration and mechanical resistance would be limiting to root growth at pF 2.3 and pF 3.0 respectively. The results obtained in this experiment appear to correlate well with those obtained by Eavis (1972) in a sandy loam soil (Figure 7.1) in which aeration is limiting growth at low pF values but is overriden by mechanical resistance at higher matric suctions.

CHAPTER 8

AMELIORATION OF THE PHYSICAL PROPERTIES OF TAILINGS

8.1 INTRODUCTION

The results of the glass house experiments and the soil strength and aeration studies, together with the results of physical analyses in Section 5.4, highlight the undesirable physical properties of tailings for plant growth.

In view of the unsuitability of the tailings for plant growth further studies were undertaken to investigate the amelioration of the tailings with organic and inorganic substances and topsoil in an attempt to create a more favourable environment for plant establishment.

The glass house amendment experiments,with the exception of the perlite amendment trials were conducted by Mr Robert Adam at the University of New England. The experimental design was based on the physical and chemical analyses which were conducted by the writer. The results were statistically analysed by Mr Adam, however, the interpretation of the results was undertaken by the writer.

8.2 MATERIALS AND METHODS

The tailings material was collected and prepared as described in Section 5.2. The 100% sands and 50% sands:50% slimes (hereafter referred to as sands/slimes) fractions were selected for the experiment. The sands/slimes fraction was chosen in place of the 100% slimes fraction because of the unsuitability of the latter as a medium for plant growth, in particular, the very limited matric suction range favouring growth (Figure 7.3).

Japanese millet (*Echinochloa utilis*) was used as the indicator species in the perlite amendment pot trial but unfortunately was unavailable when the other amendment trials were conducted. Oats (*Avena Sativa* c. v. Cooba) was used for these pot trials. Both species are cereal crops and their growth responses would not be expected to be substantially different. To ensure adequate nutrients for plant growth "Thrive" plant food (a liquid fertilizer) was applied at the manufacturers recommended rate at sowing and subsequently at two week intervals. The chemical composition of the liquid fertilizer is shown in Table 8.1. Japanese millet and oats were also grown in a chocolate soil and the two tailings mixtures for comparison.

Table 8.1 Chemical Composition of Liquid Fertilizer Applied to Treatments
(After : Arthur Yates and Co Pty Ltd Milpera,N.S.W.)

Element	% content of solution
Nitrate nitrogen	2.6
Nitrogen as ammonia	2.2
Nitrogen as urea	26.2
Phosphorus-water soluble	4.57
Potassium as potassium nitrate	8.71
Magnesium as magnesium sulphate	0.12
Sulphate sulphur	0.064
Copper as copper sulphate	0.005
Zinc as zinc sulphate	0.02
Boron as sodim borate	0.005
Manganese as manganese sulphate	0.04
Molybdenum as sodium molybdate	0.002

The amendments, their treatment levels and quantity added per pot are shown in Table 8.2. The lucerne chaff and the commercially available peatmoss were ovendried for 24 hours at 75°C, the lucerne chaff was subsequently chopped in lengths not >5 mm. The soil amendments was the topsoil of a chocolate soil, as previously used and described in Section 6.2.2. The polyvinyl alcohol (P.V.A.) was a commercial grade (P.V.A. 20) manufactured by the Shiretsu Chemical Company. The gypsum was a commercial grade gypsum, which is used as an amendment on sodic soils.

Table 8.2 Amendment Treatment Levels and Quantity Applied per Pot

Lucerne Chaff		Peatmoss		Soil		P.V.A.		Gypsum		Perlite
(t ha^{-1})	(g pot^{-1})	(t ha^{-1})	(g pot^{-1})	(t ha^{-1})	(g pot^{-1})	(%)	(g pot^{-1})	(t ha^{-1})	(g pot^{-1})	Volume % of pot
5	3.57	5	3.57	100	71.4	0.5	7.5	5	3.57	10
10	7.14	10	7.14	200	142.8			10	7.14	25
25	17.85	25	17.85	400	285.6			20	14.28	50
50	35.70	50	35.70	600	428.4			50	35.70	

Perlite was separated into three size fractions: <2 mm
2-5 mm
unsieved sample

Treatments were replicated 3 times.

Perlite is a generic term for naturally ocurring siliceous volcanic rock. Thompson and Reed (1954) have described the source material in New Zealand to be acid volcanic glassy rhyolites from the Taup - Rotorua and Tairua districts. The distinguishing feature which sets perlite apart from other volcanic glasses is that when it is heated to a suitable point in its softening, it expands 4 to 20 times its original volume. When heated quickly to above 830°C the 2 to 6% water in the rock vaporizes and the rock pops, similar to popcorn, creating countless tiny bulbs in the heat softened glassy particles (Anon, 1983).

Perlite is a light weight material which has many uses, including use as a filler in potting mixtures for horticultural purposes, gypsum, acoustical plastics and insulating concrete. Because of the light weight nature of the material and its vesicular structure it was considered that it would be a suitable amendment material. The chemical composition of perlite, as supplied by Australian Perlite Pty Ltd is shown in Table 8.3. It is white in colour, having a particle density of 2.2-2.4 g cm^{-3} and a bulk density of 0.32-0.40 g cm^{-3}. The bulk density can be altered by the degree of heating during formation (Anon, 1983).

Table 8.3 Chemical Composition of Perlite
(After : Anon, 1983)

Chemical	% by weight
SiO_2	75.00 - 77.00
Al_2O_2	12.50 - 13.50
K_2O	5.20 - 5.70
Na_2O	3.12 - 3.16
Fe_2O_3	1.30 - 1.50
CaO	0.58 - 0.62
MgO	0.08 - 0.12
TiO_2	0.14 - 0.16

Three size fractions of perlite were prepared. A <2 mm size and a 2-5 mm size fraction by sieving and an unsieved sample.

The lucerne chaff, peatmoss, soil, gypsum and perlite treatments were mixed with the tailings mixtures in a revolving cement mixer. The P.V.A. solution, which was achieved by dissolving an equivalent amount of 7.5 g pot^{-1} in boiling water was sprayed onto the drying tailings in a revolving cement mixer. The P.V.A. mixtures were then placed in trays and oven dried for 48 hours at 75°C. The material was then broken into aggregates to a maximum of 10 mm dia.

1,500 g of each mixture was placed in polythene lined 15 cm pots as for previous pot experiments (Chapter 6). However, for the perlite treatments only 750 g of tailings was used because of the increased volume attained when the perlite was added. The pots were sown, fertilized, watered , sealed and the experiments conducted as previously described (Section 6.1.2).

All pots, except for the perlite treatments were harvested 6 weeks after emergence, photographs taken, shoots and roots separated, weighed and statistically analysed. Plants in the perlite treatments were harvested 4 weeks after emergence as they had begun to wither. The plants may have survived for a longer time, but because this experiment was for observational purposes only and yields were not statistically analysed, the time of harvesting as compared to other treatments was not important. Selected root photographs were taken.

8.3 RESULTS

Mean results for all treatments excepting the P.V.A. and perlite are presented in graphical form. The degree of statistical significance is also shown. Photographs showing the comparison between treatment levels are also given.

Root development in both tailings mixtures in all treatments and treatment levels display clubbed tips, limited lateral development and swollen root sections (Plates 8.1-8.10). In addition, primary root growth direction has been changed noticeably on a number of occassions, as indicated by the sharp bends in the roots.

8.3.1 Organic Amendments - Lucerne Chaff and Peatmoss

8.3.1.1 Lucerne Chaff

The results for the lucerne chaff treatment are shown in Figure 8.1 and the root morphologies in Plates 8.1 and 8.2. There was an initial decrease in dry matter yield for both tailings fractions at the 5 t ha^{-1} treatment level and in the sands/slimes mixture yield did not vary significantly at the higher treatment levels. There was a significant ($P<0.05$) increase in yield at the 50 t ha^{-1} treatment level for the 100% sands fraction.

The increased lateral root development with increasing rates of lucerne chaff was noticeable in the sands but this increase in root density is in contrast to that in the sands/slimes mixture where there was no marked increase in development with additional quantities of lucerne chaff.

8.3.1.2 Peatmoss

Peatmoss had no significant effort on plant growth in the 100% sands fraction (Figure 8.2).

Following an initial decline in growth at the 5 t ha^{-1} treatment level in the sands/slimes mixture growth increased with additional quantities of peatmoss and was significant ($P<0.05$) at the 25 t ha^{-1} and 50 t ha^{-1} treatment levels.

Increased primary and lateral root development corresponds to increased levels of peatmoss in both fractions (Plates 8.3 and 8.4). The primary root growth of plants in the sands/slimes mixture is superior to that of plants grown in the 100% sands fraction, however, lateral root growth and root abnormalities are common to roots grown in both mixtures.

8.3.2 Chemical Amendments - P.V.A. and Gypsum

8.3.2.1 P.V.A.

The growth of plants in the P.V.A. treated fractions was superior to those of the tailings control treatments (Plate 8.5). There was no statistical difference between the yields of the sands/slimes and 100% sands mixtures. Whilst increased dry matter yield was obtained over the two tailings control treatments there were noticeable restrictions in root growth, as indicated by the reduced lateral development and root abnormalities.

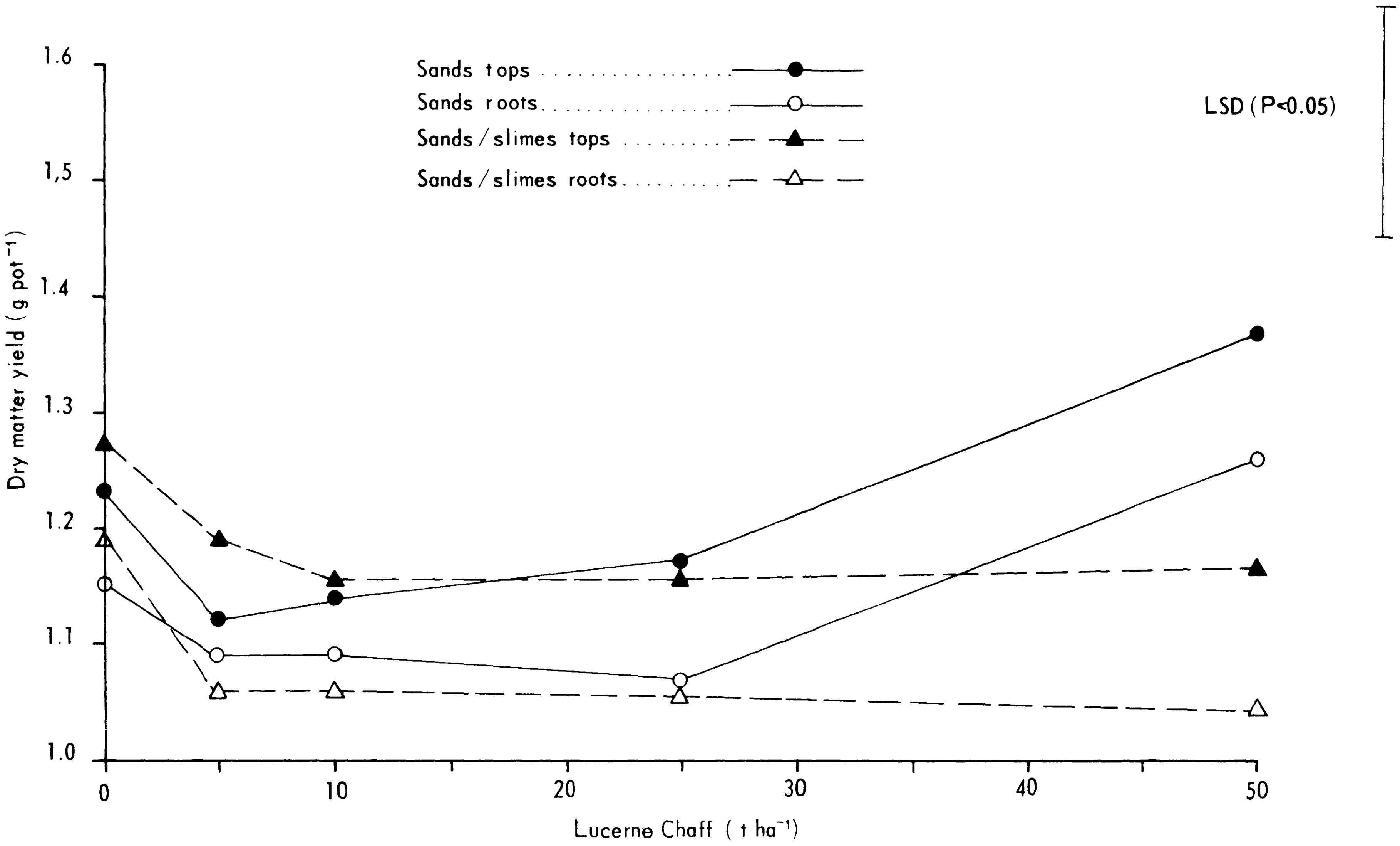


Figure 8·1 Effect of Lucerne Chaff Addition to Tailings Mixtures on the Dry Matter Yield of Oats.

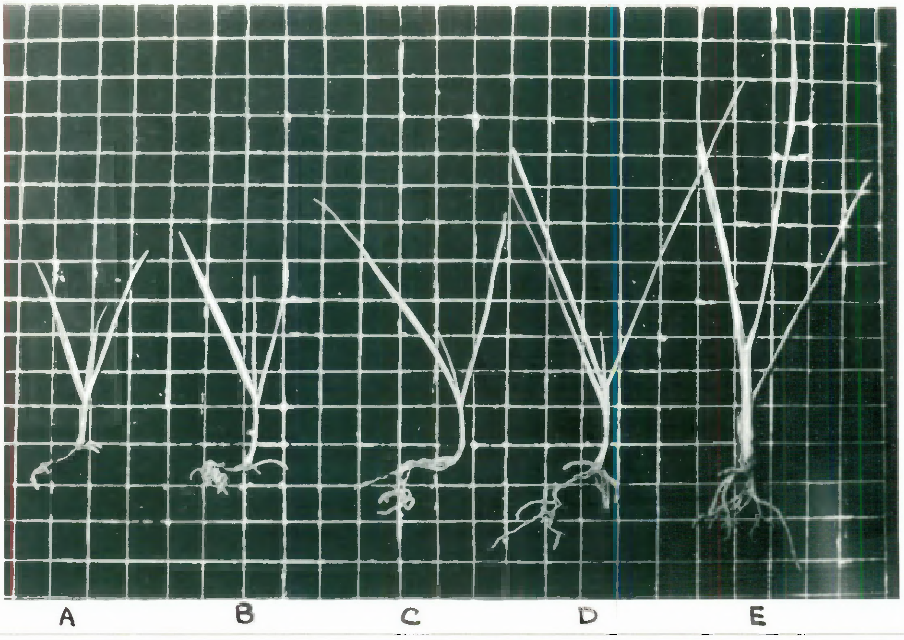


Plate 8.1: Growth of oat plants in the sands tailings fraction with increasing amounts of lucerne chaff.

A = Sands tailings control
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 25 t ha^{-1}
E = 50 t ha^{-1}

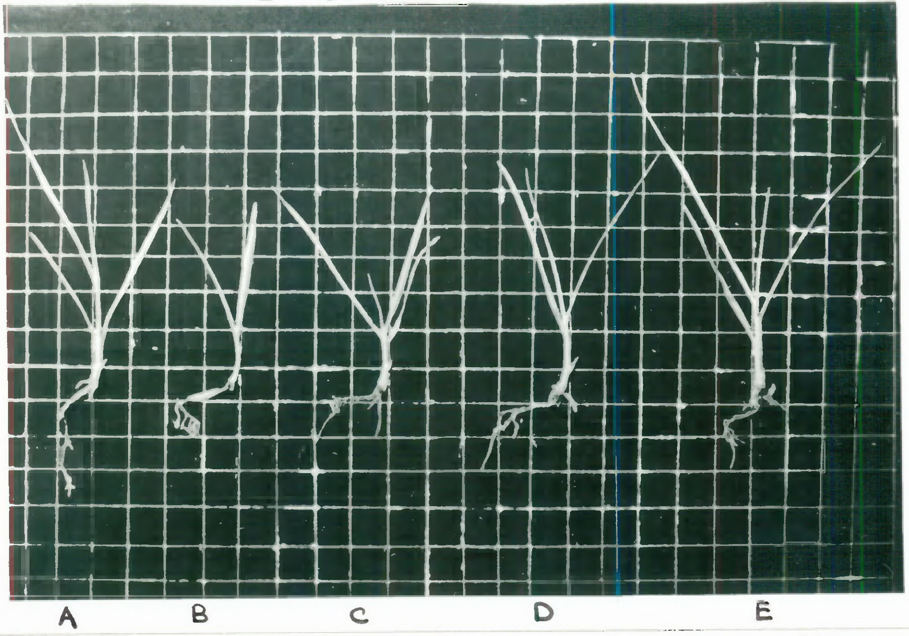
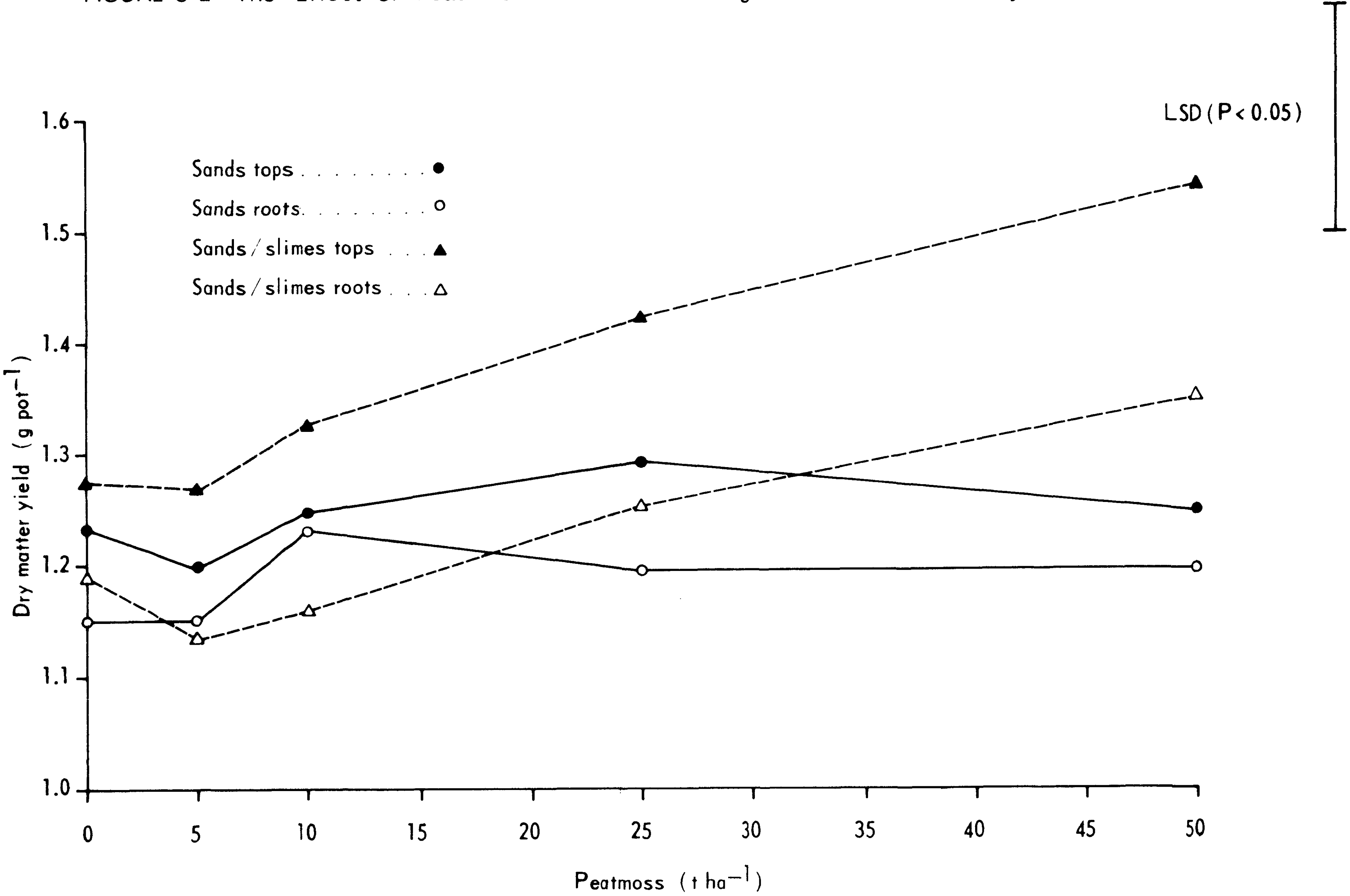


Plate 8.2: Growth of oat plants in the sands/slimes tailings mixture with increasing amounts of lucerne chaff.

A = Sands/slimes tailings control
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 25 t ha^{-1}
E = 50 t ha^{-1}

FIGURE 8·2: The Effect of Peatmoss Addition to Tailings Mixtures on the Dry Matter Yield of Oats.



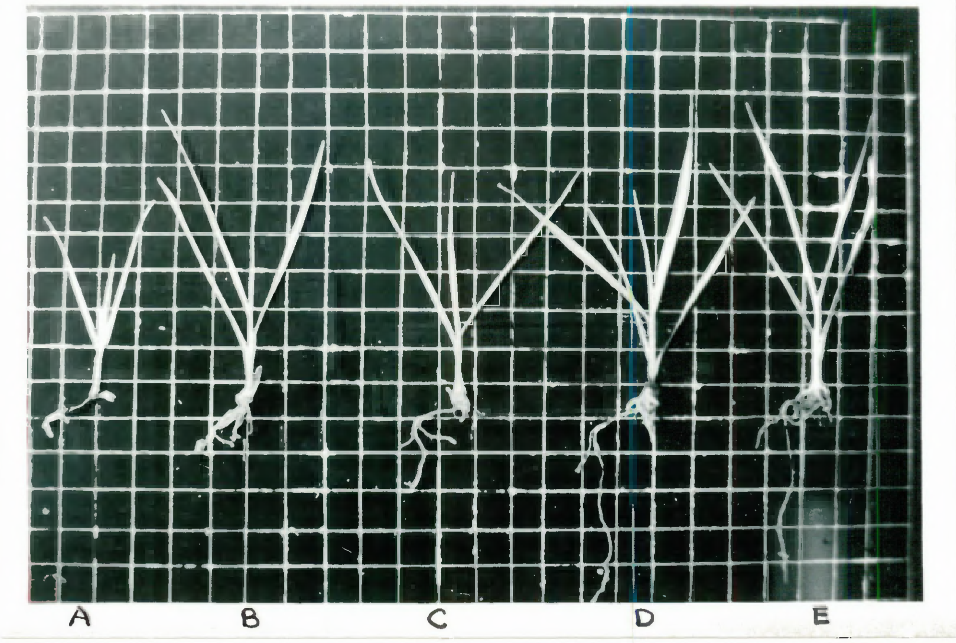


Plate 8.3: Growth of oat plants in the sands tailings fraction with increasing amounts of peatmoss.

A = Sands tailings control
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 25 t ha^{-1}
E = 50 t ha^{-1}

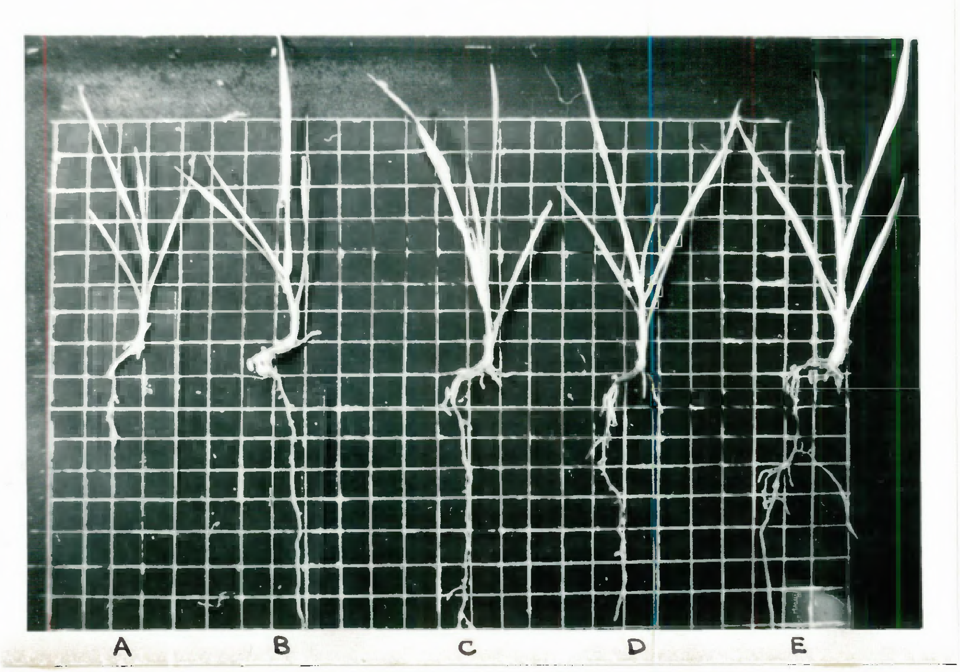


Plate 8.4: Growth of oat plants in the sands/slimes tailings mixture with increasing amounts of peatmoss.

A = Sands/slimes tailings control.
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 25 t ha^{-1}
E = 50 t ha^{-1}

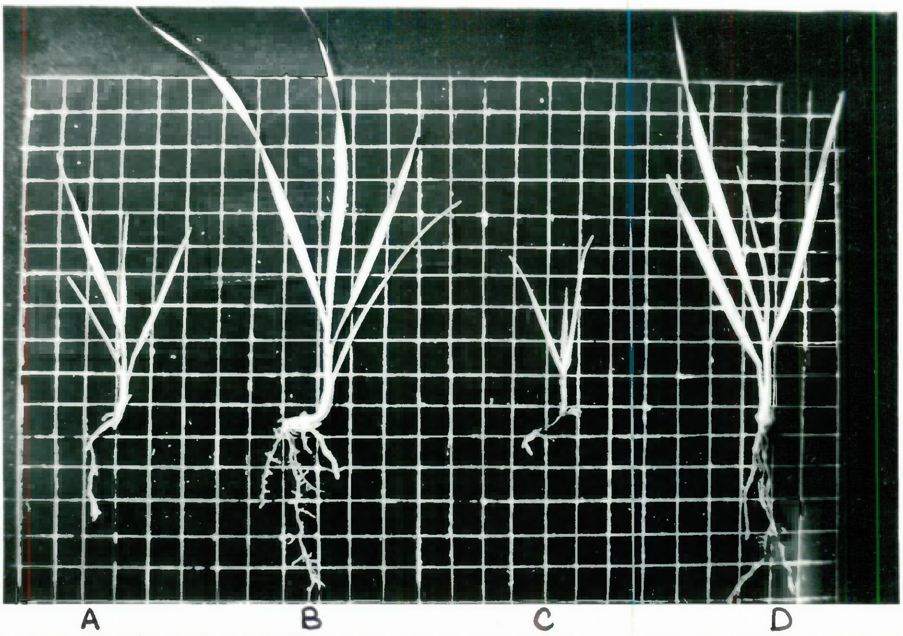


Plate 8.5: Growth of oat plants in the sands and sands/slimes tailings mixtures with 0.5% P.V.A.

A = Sands/slimes tailings control
B = Sands/slimes with P.V.A.
C = Sands tailings control
D = Sands with P.V.A.

8.3.2.2 Gypsum

The results for the gypsum treatments are shown in Figure 8.3. There was an initial decrease in dry matter yield at the 5 t ha^{-1} treatment level for both tailings mixtures. Higher applications of gypsum, up to 50 t ha^{-1} did not significantly increase the growth of roots or shoots in either of the mixtures (Plates 8.6 and 8.7).

8.3.3 Soil

The addition of soil had no significant effect on plant growth in the 100% sands fraction (Figure 8.4). However, it significantly increased ($P<0.05$) growth of roots and shoots at the two higher treatment levels, 400 and 600 t ha^{-1}, in the sands/slimes mixture.

The root morphologies of plants grown in both mixtures (Plates 8.8 and 8.9) show very marked abnormalities, with clubbed tips and swollen root sections being noticeable. It is only at the 600 t ha^{-1} treatment in the 100% sands mixture that significant root growth is evident. However, even at this treatment level root growth is still restricted. Increasing quantities of soil in both mixtures increased root growth. At the lower treatment levels (100,200 and 400 t ha^{-1}) in the 100% sands mixture root growth was severely restricted.

8.3.4 Perlite

Growth in both tailings mixtures and at all treatments was poor. There was, however, a visible difference between the treatments of perlite but not between the tailings mixtures. The plants in the mixtures containing <2 mm size perlite commenced to wither at an earlier time than other treatments. There was however, no noticeable difference in plant performance between the 10, 25 and 50% volume treatments.

Plant performance in the mixtures containing 2-5 mm perlite was superior to that on adding <2 mm perlite. Plants were more vigorous in growth, but only reached a height of 18 cm before withering and dying from the tips. This was approximately 8 cm higher than the plants in the <2 mm perlite treatments. For the 50% perlite addition, plant performance was marginally, but not significantly, better than those at the 10 and 25% treatment levels.

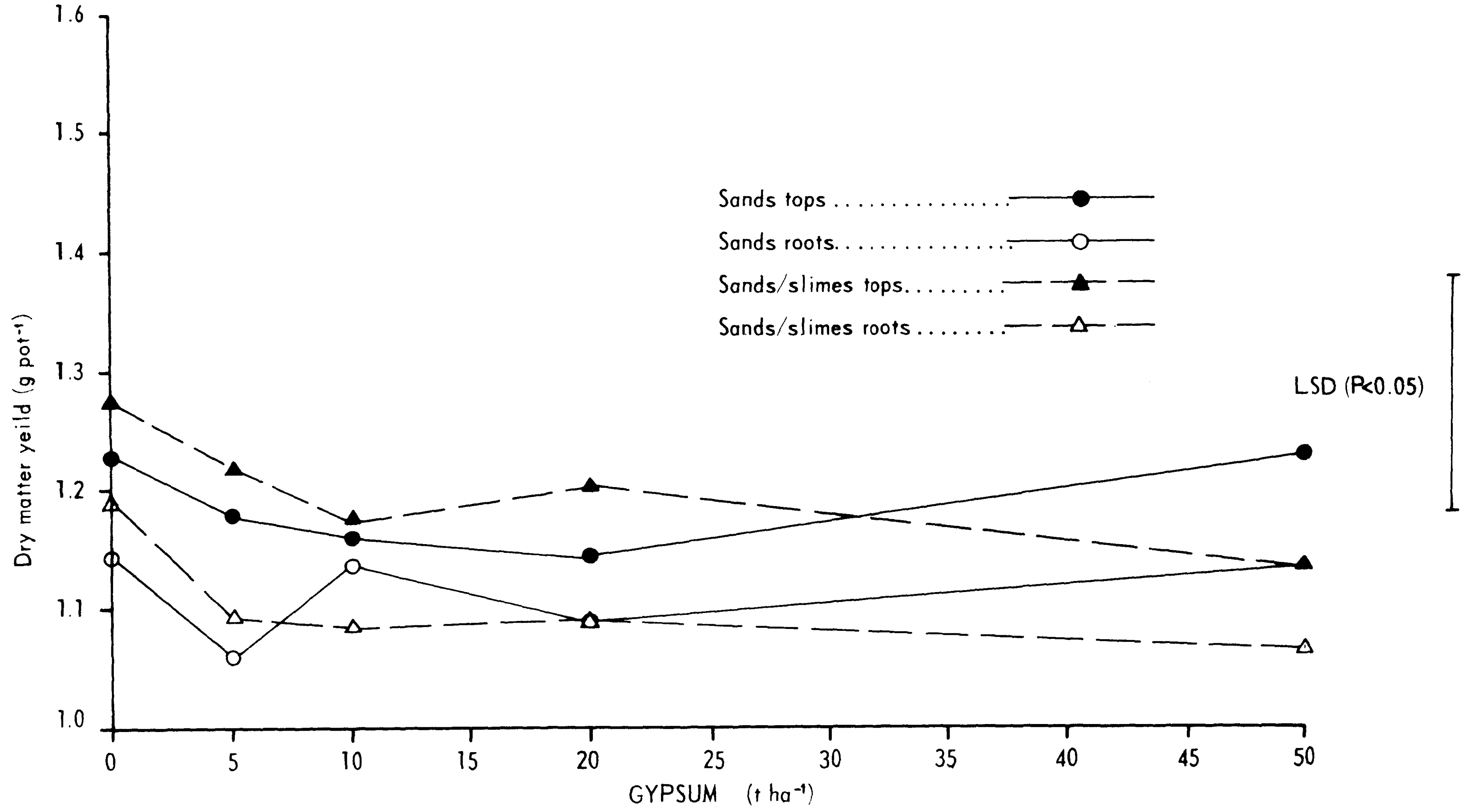


Figure 8·3 Effect of Gypsum Addition to Tailings Mixtures on the Dry Matter Yield of Oats.

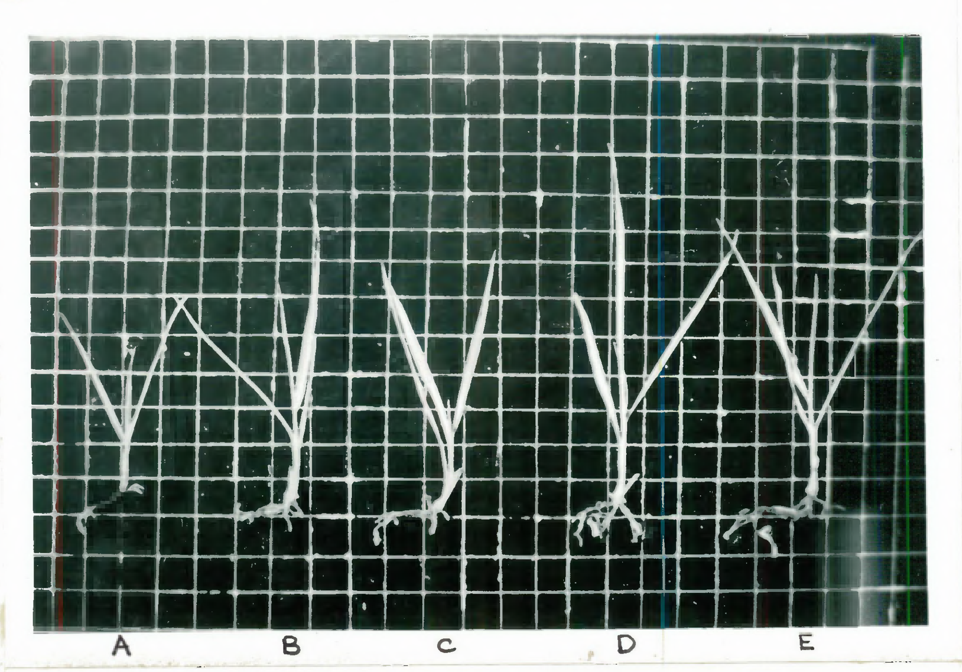


Plate 8.6: Growth of oat plants in the sands tailings fraction with increasing amounts of gypsum.

A = Sands tailings control
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 20 t ha^{-1}
E = 50 t ha^{-1}

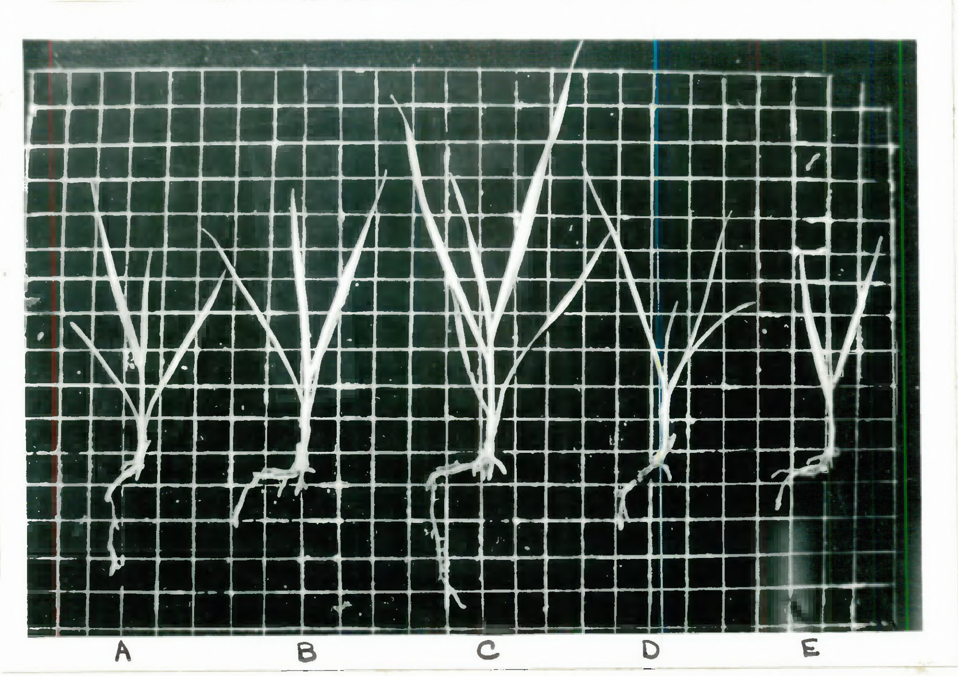


Plate 8.7: Growth of oat plants in the sands/slimes tailings mixture with increasing amounts of gypsum.

A = Sands/slimes tailings control
B = 5 t ha^{-1}
C = 10 t ha^{-1}
D = 20 t ha^{-1}
E = 50 t ha^{-1}

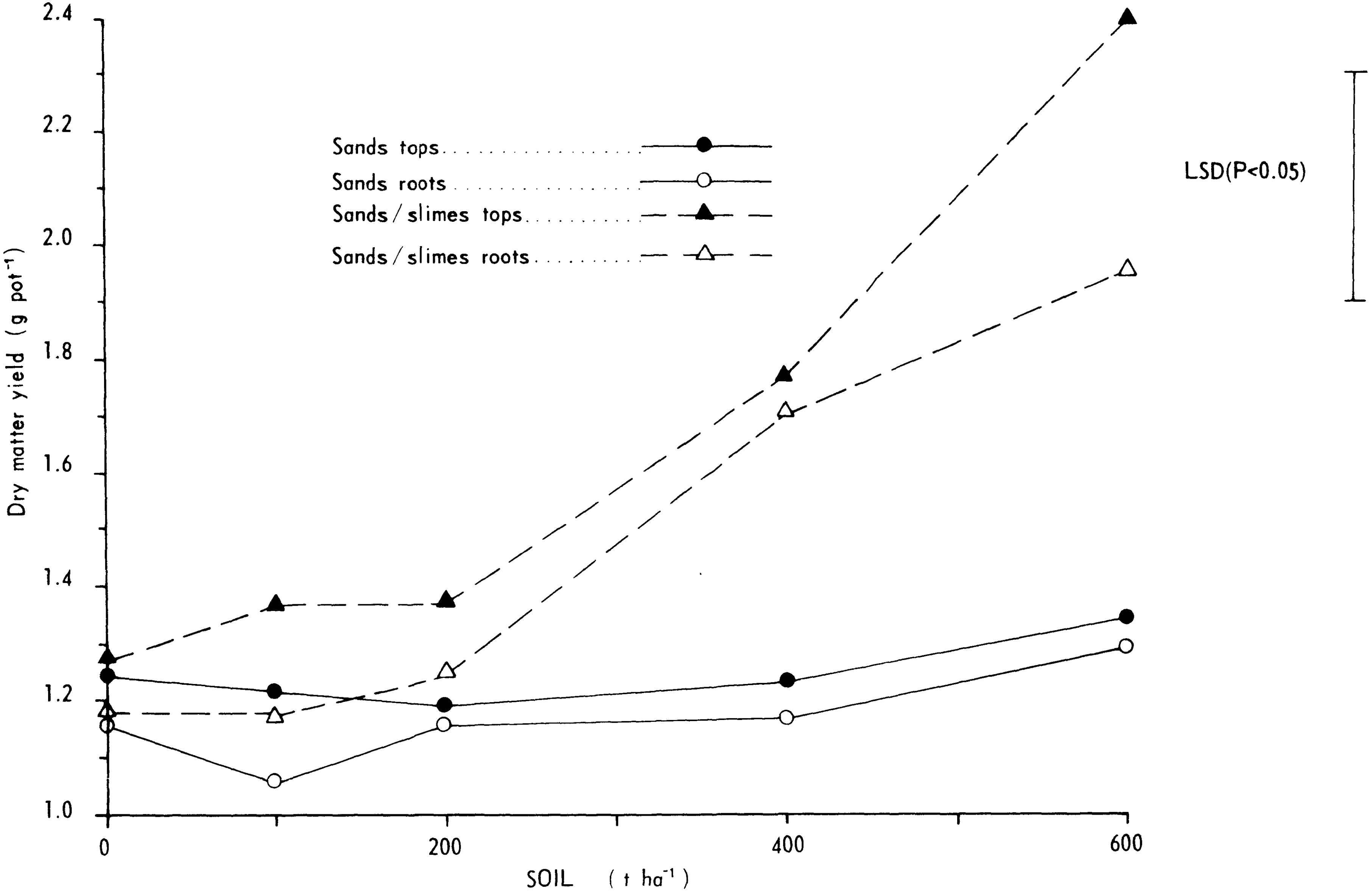


Figure 8·4 Effect of Soil Addition to Tailings Mixtures on the Dry Matter Yield of Oats.

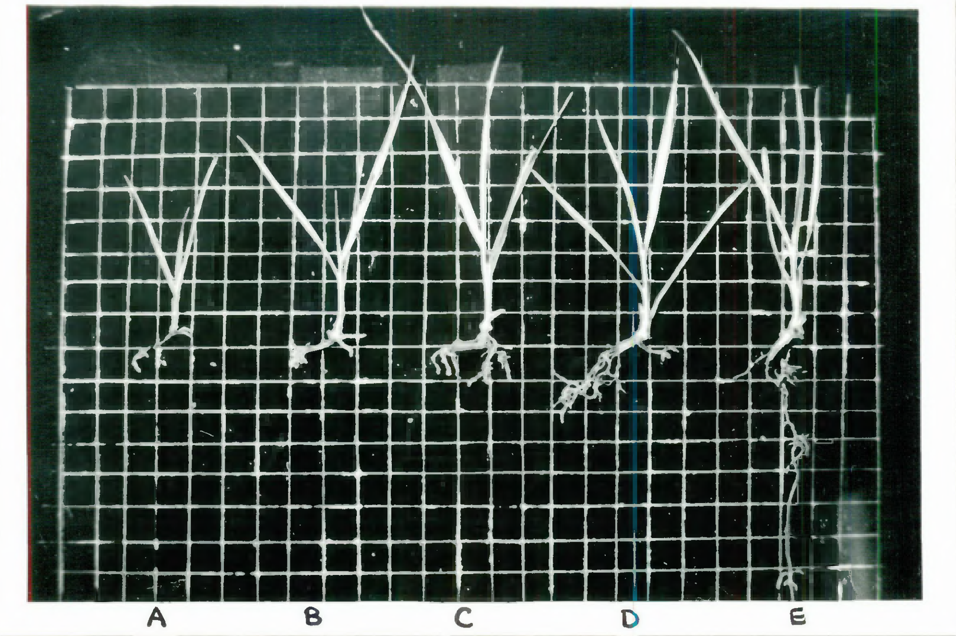


Plate 8.8: Growth of oat plants in the sand tailings fraction with increasing amounts of soil.

A = Sands tailings control.
B = 100 t ha^{-1}
C = 200 t ha^{-1}
D = 400 t ha^{-1}
E = 600 t ha^{-1}

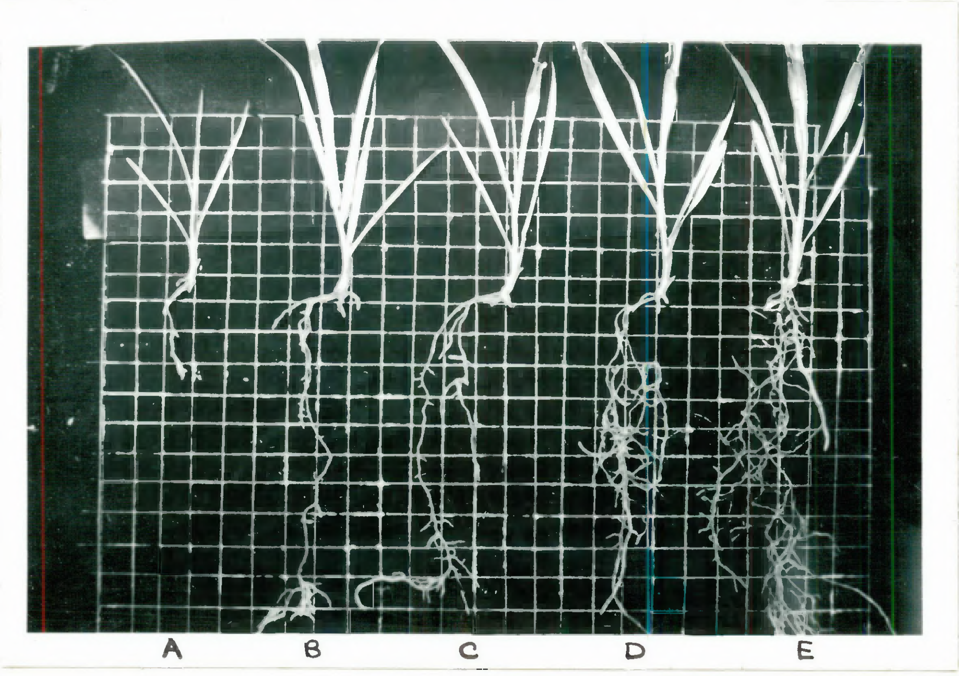


Plate 8.9: Growth of oat plants in the sands/slimes tailings mixture with increasing amounts of soil.

A = Sands/slimes tailings control.
B = 100 t ha^{-1}
C = 200 t ha^{-1}
D = 400 t ha^{-1}
E = 600 t ha^{-1}

The growth of plants in the unsieved perlite treatments was marginally better than in the <2 mm perlite treatments, but was inferior to that in the 2-5 mm treatments. However, the 50% treatment with the unsieved perlite gave a similar plant response to that of the 2.5 mm, 50% treatment.

The roots of plants grown in all treatments in both tailings mixtures displayed significant root abnormalities. Lateral root development was slightly better in the 50% 2-5 mm and 50% unsieved perlite treatments than in other treatments (Plate 8.10).

Plate 8.11 shows the morphology of a Japanese millet root grown in the 100% sand control mixture as viewed under a microscope. Very small lateral development has commenced but this is confined to the convex side of the root. The root has changed direction on at least two occasions as signified by the bend in the root, some 4 cm from the tip. The shape of the tips of roots which have been grown in a 100% sand tailings mixture and a chocolate soil from the "Kirby" research farm as viewed under a microscope are compared in Plate 8.12. The root grown in the 100% sands mixture has a clubbed or swollen tip while the root grown in the chocolate soil has a pointed tip. Plate 8.13 shows a root from the sands/slimes mixture control which displays significant root hair development.

8.4 DISCUSSION

The experiments show that none of the treatments were able to ameliorate the adverse conditions in the tailings and that the abnormal development of roots has persisted. It would appear that the interrelationship between mechanical resistance,water potential and aeration as depicted in Figures 7.2 and 7.3 and by the work of Hopkins and Patrick (1970) Voorhees *et al.* (1975) and Eavis (1972) is typified by the poor growth and root morphologies of the plants grown in all treatments.

The significant increase in plant performance in the 100% sands mixture with the addition of 50 t ha^{-1} of lucerne chaff is possibly due to the more favourable pore size and pore size distribution created, compared to other treatment levels. Pore size is important as roots in a rigid medium cannot enter pores smaller than their own diameter even

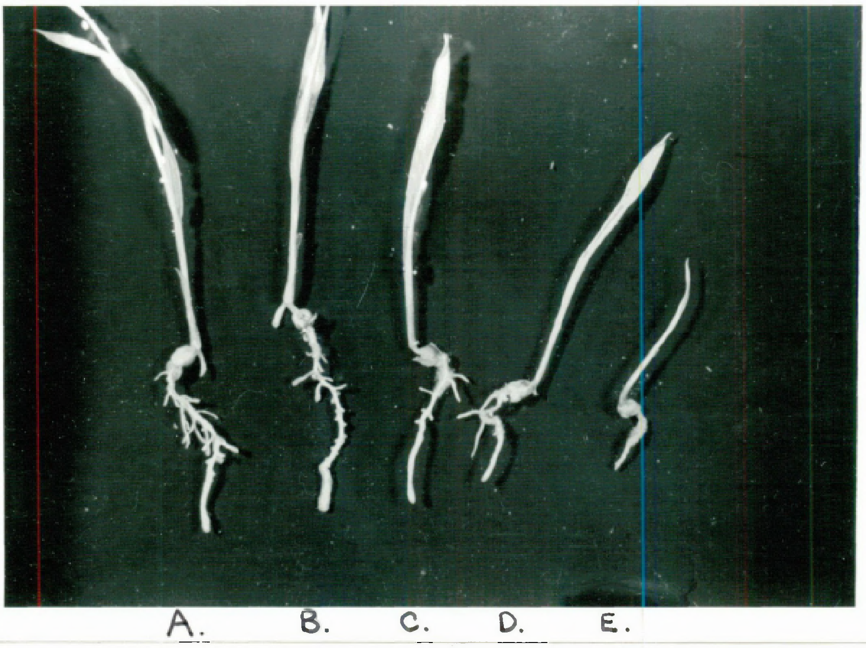


Plate 8.10: Growth of Japanese millet in the sands tailings fraction with different treatments of perlite.

A = 50% of 2-5 mm
B = 50% of unsieved
C = 50% of <2 mm
D = 25% of 2-5 mm
E = Sands tailings control

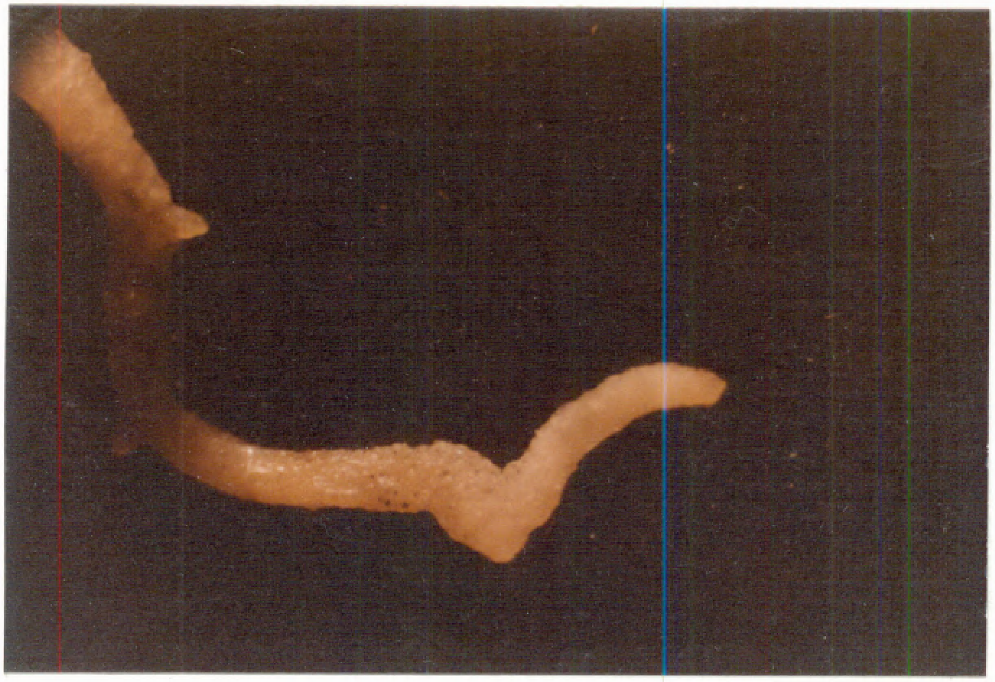


Plate 8.11: Morphology of a Japanese millet root grown in the sands tailings fraction as viewed under a microscope. Note, the growth of lateral roots is confined to the convex side of root bends. Note also, the abrupt change in root direction.

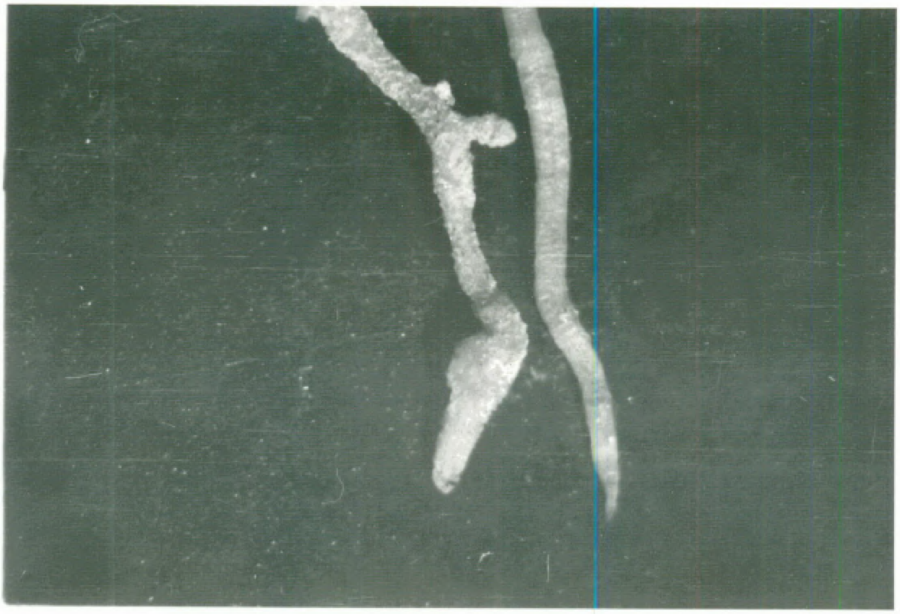


Plate 8.12: Comparison of root tip morphology of Japanese millet grown in the sands tailings fraction (left), and "Kirby" soil (right). The former shows a distinct clubbed tip.

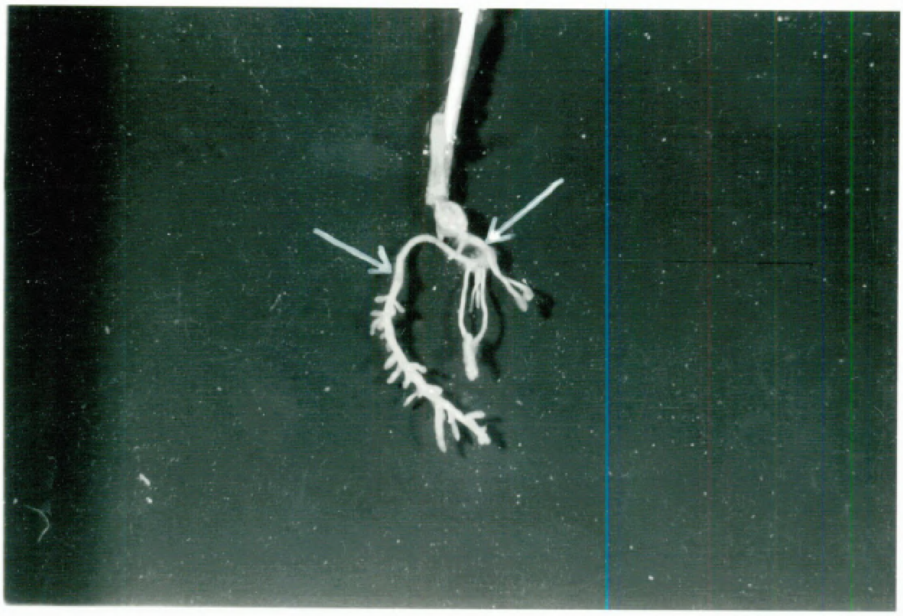


Plate 8.13: Proliferation of root hairs on a Japanese millet root grown in the sands tailings fractions.

if apices gain entry (Wiersum, 1957; Russell and Goss, 1974). However, Schuurman (1965) found that the roots of oats with a diameter of 150 to 308 μm entered small pores but not those smaller than 205 μm in a humus sand packed at bulk densities of 1.24, 1.38 and 1.52 g cm^{-3}. This implies that the root can exert a force and widen a pore to a diameter permitting growth in compact soils. Pfeffer (1893) found that roots could exert longitudinal measures of about 10 bar and radial pressures of 6 to 7 bar. Gill and Miller (1956), Barley (1962) and Taylor and Ratliff (1969a) showed that roots could exert longitudinal pressures of between 9 and 13 bar. Russell discusses the ability of roots to penetrate pores and concludes that not only can roots not enter pores which are smaller than themselves but they usually increase in size with increasing mechanical resistance. The clubbed tips and swollen root sections in the roots of plants grown in the tailings and tailings with amendments (Plates 8.1-8.13) would indicate that mechanical resistance has influenced the root morphologies.

Roots may still be encased by tailings despite the addition of ameliorants. This has resulted in the tailings retaining its high strength and roots have been unable to break through and develope normally.

The addition of organic matter with subsequent humification and incorporation with the mineral fraction in conjunction with root penetration leads to aggregation and void formation (Payton, 1980). The tailings are very low in organic matter (Table 5.2) and with the well graded nature of the particles (Table 5.8) there would be a great tendency for the material to pack and create smaller pores especially under high matric suctions. The shape of the particles also predisposes the tailings to packing, as previously discussed in Section 7.2.3. Organic matter and in particular humic bands are important for soil structure (Blake, 1967). However, it is not so much the total amount of organic matter which is important but, rather the type of organic matter compounds and their bonding properties (Russell, 1977).

The failure of the lucerne chaff treatments in the sands/slimes mixture and other treatments in both mixtures, such as the perlite and peatmoss, could be due to anaerobic conditions. The possibility of anaerobes would have been increased due to the lack of control of watering.

Whilst the pots were watered daily, they were not weighed to determine the water requirements to bring the pots to field capacity. Over watering could have easily resulted as the pots were polythene lined and hence undrained. The very low air filled pore space in the sands and slimes at low matric suctions (Figures 7.2 and 7.3) predisposes plants to restricted growth, especially when the air filled porosity is <10% (Wesselling and van Wijk, 1957).

When gas exchange is restricted and anaerobic metabolism proceeds in the soil, the concentration of CO_2 increases (Russell, 1977). However it diffuses more rapidly than oxygen in solution because of its greater water solubility (Greenwood, 1970). Whilst high CO_2 levels can be toxic to plants it is a minor source of injury as compared to a lack of O_2 (Krammer, 1969) and would not be expected to be a major problem in the tailings.

Whilst low concentrations of oxygen can severely restrict root growth (Greenwood, 1969) the production of organic acids in anaerobic soils (Stevenson, 1967) and the hydrocarbon gases, such as methane and ethylene can affect plant growth (Smith and Russell, 1969; Smith and Restall, 1971). Ethylene can be produced by various fungi (Bird and Lynch, 1972).

The reason for the oven drying of the peatmoss is not known, but this was a mistake as the water holding properties of the peatmoss and its interaction with the tailings would be altered. The uniform and relatively small length to which the chaff was chopped created an artificial situation and one which would be unlikely to be reproduced under field conditions. The pore size may have been more favourable if chaff of differing sizes had been used.

The oven drying of the peatmoss with its possible effect on the hydroscopic properties of the material would lead to close packing in the tailings. The very small and deformed roots in the 100% sands peatmoss treatments (Plate 8.3) would suggest that pore size was limiting. In the sands/slimes mixture peatmoss treatment the significant increase in root growth was due to the length of the primary root. This suggests that the peatmoss may have created small zones of weakness through which the roots could move but due to the surrounding compactness laterals could not develop (Plate 8.4).

Increased soil strength at high matric suctions due to particle rearrangement and a subsequent increase in the degree of packing could be expected with both fractions as indicated by the results in Figures 7.2 and 7.5. Mullins and Panayiolopoulos (1980) found that bulk density increased when coarse and find sand was mixed together. Hopkins and Patrick (1970) found that at high compaction levels root penetration was so limited by mechanical impedance that O_2 levels had little effect. Gross root morphological effects in response to increased soil physical resistance have been noted by numerous workers (Gill and Miller, 1956; Wiersum, 1957; Barley, 1962; 1963; Greacen and Oh, 1972; Russell and Goss, 1974; Voorhees *et al.*, 1975; Goss, 1977; Wilson *et al.*, 1977). Voorhes *et al.* (1975) found that as soil resistance increased the primary root became more twisted and the length ratio of first order laterals to primary root increased. Gerard *et al.* (1972) made similar observations. The harvested roots from this set of pot experiments and those discussed in Section 6.1.4 did not produce the same lateral to primary root ratio. It is very noticeable that lateral root growth was initiated but presumably due to mechanical resistance and or restricted aeration they failed to develop. With increasing applied pressure (0.1-0.5 bar) On the roots of Barley (*Hordeum vulgare* L.) grown in beds of ballotini, Russell and Goss (1974) found that the length of the primary and lateral root were decreased and visibly enlarged in diameter.

The response of lateral roots to high soil strength has been less studied than that of primary root axes. However, Russell and Goss (1974) found they reacted very similar provided the pore diameter was so small that axes and laterals were both subjects to mechanical impedance. Goss (1974) found that an applied pressure of 0.5 bar severely restricted the growth of both primary and lateral roots when grown in a well aerated solution whith ample nutrients applied. He also noted that mechanical impedance had caused the root hairs to proliferate. The poliferation of root hairs was also noted in the pot experiments conducted by the writer (Plates 6.2, 6.3 and 8.13), being further evidence that mechanical impedance was a major cause of the root abnormalities and the subsequent reduced plant growth.

Hypertrophy of roots similar to that found by Russell and Gross (1974) and by the writer (Plates 6.1-6.4 and 8.1-8.13) has also been noted by Hottes (1929) and Gupta (1933). Schuurman (1965) found hypertrophy was very evident in the roots of oats when they attempted to penetrate a layer of higher density, he also noted a similar effect at sharp pH transitions. Plates 6.5, 8.11, and 8.12 show the hypertrophy effect in roots grown in tailings compared to roots grown in an agricultural soil.

Even with the incorporation of high rates of soil (600 t ha^{-1}) with the 100% sands fraction root growth was very restricted (Plate 8.8) while it was only at the 600 t ha^{-1} level in the sands/slimes mixture that a marked increase in root extention was evident. Much of the primary root growth was noted growing within soil particles. Fontaine (1959) states that roots may have to apply a pressure of 1-3 bar to their surroundings to grow within clods.

P.V.A. is known to aid aggregation. Suneja *et al.* (1982) found with the addition of 0.05% P.V.A. to a loam soil (clay 18.6%, silt 17.0%, sand 64.4% and organic matter 0.67%) they achieved a significant improvement in structure, measured by mean weight diameter and water stable aggregates. However, it did not produce significant results in the tailings mixtures as indicated by the root deformation.

The lack of response to the application of gypsum is not surprising considering the low E.S.P. (Table 5.4) of the tailings and that during saturated hydraulic conductivity experiment (section 5.4.4) the clay was not dispersed.

The microscopic examination of the roots (Plates 8.11 and 8.12) reveals further evidence to suggest that mechanical impedance was a major factor operating to produce the root abnormalities. When mechanical obstructions cause roots to curve, laterals are typically laid down on the convex side of the radicle (Snow, 1905). This phenomenon is displayed in Plate 8.11.

The results of this set of experiments would suggest that the addition of amendments to the tailings in a field situation would not sufficiently alter the physical characteristics of the tailings sufficiently to achieve the establishment of an adequate vegetative cover. The results also show the need for a controlled watering regime when polythene liners are used. The possibility of anaerobic conditions could have been eliminated by pricking the bottoms of the polythene liners following germination.

CHAPTER 9

CONCLUSIONS

The analyses and pot experiments have highlighted the harshness of the tailings material for vegetative establishment. Chemical analyses show the tailings to have low levels of phytotoxic substances, to be low in organic matter and nitrogen, with other necessary nutrients for plant growth to be in adequate supply. Any attempt to establish vegetation would require the application of nitrogeneous fertilizers. The results of the antimony analyses and pot trials failed to reveal any phytotoxic effects.

The particle size distribution and particle shape predisposed the tailings to packing. The moisture characteristics show a reasonably good available moisture capacity. However, the limited air filled pore space at field capacity (pF 2.4) indicates that aeration could be a problem for plant growth.

The failure of plants to establish and grow past the two leaf stage when grown in the tailings mixtures and the similar results achieved with the addition of topsoil, inorganic and organic amendments emphasised the unsuitability of the tailings for plant growth. The gross root morphological effects, and in particular, the hypertrophy and reduced primary and lateral root development were the reasons for the failure of the plants to survive. Further analyses showed that at field capacity, the tailings had an air filled porosity <10%, so that at low matric suctions anearobic conditions may exist. At higher suctions however, mechanical resistance, as measured by a penetrometer, increased to such levels as to restrict root growth. The effects of mechanical resistance and limited aeration have resulted in a limited suction range favouring growth. This range is pF 2.3-3.0 in the sands and pF 2.8-3.0 in the slimes tailings fractions.

It would not be possible under field conditions to maintain the tailings in the moisture range which favours growth. The establishment of vegetation in the tailings as a means of rehabilitation is therefore not practicable. The most favoured method of rehabilitating the tailings dumps is to cover them with a layer of topsoil and establish a stand of self sustaining vegetation. The depth of topsoil to be used would require investigation. However, based on the writers experience with the tailings and the surrounding undisturbed environment, together with the work of other researchers (Section 2.4.1), a topsoil blanket of 30-40 cm thickness should prove satisfactory. Whilst the vegetative species would require investigation, a combination of introduced perennial grasses and legumes would be required for initial cover and protection, and perennial native grasses and shrubs for long term maintenance free stabilization. The species identified growing in the area (Section 3.5) should be included in any vegetative recommendations.