ASSESSING THE COMPACTION SUSCEPTIBILITY OF SOUTH AFRICAN FORESTRY SOILS

by

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DECLARATION

I hereby certify that this research is the result of my own investigation, except as acknowledged herein, and that it has not been submitted for a higher degree in any other university.

C W SMITH

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ABSTRACT

The widespread use of heavy machinery during harvesting and extraction operations in South African timber plantations has led to concern that soil compaction is causing long term site productivity declines and environmental damage. This study was conducted with the intention of establishing a framework for the routine prediction of compaction susceptibility of South African forestry soils. Principal facets of compaction behaviour were established for a wide range of soils and these were related to changes in soil physical conditions resulting from compaction. Soils were chosen from a broad range of geological and climatic regions and varied greatly in texture (8 to 66% clay) and organic matter content (0.26 and 5.77% organic carbon).

A quantitative description of compaction behaviour was obtained using a simple uniaxial compression technique. Bulk density was related to applied pressure, water content and initial bulk density as independent variables. Statistical analysis of the coefficients in the model enabled the relative importance of applied pressure and water content during the compaction process to be evaluated and related to commonly measured soil physical properties.

Compressibility was strongly correlated with clay plus silt content and to a lesser extent with clay content and organic carbon determined by loss-on-ignition (LOI). Though significant correlations were obtained between maximum bulk density (MBD) and clay plus silt content, MBD was more strongly correlated with organic carbon (LOI). A classification system for compaction risk assessment is presented, based on the relationship between compactibility (MBD) and organic carbon (LOI), and between clay plus silt and compressibility.

The effect of soil compaction on soil physical quality was assessed by examining changes in penetrometer soil strength (PSS) and water retentivity curves of compacted soils. Clay content strongly influenced the relationship between PSS, bulk density and water content. The PSS at wilting point (-1500 kPa) increased with increasing clay content whereas PSS at a matric potential of -10 kPa and was most strongly related to organic carbon (LOI) and increased with increasing organic carbon content.

Compaction generally resulted in an increase in field capacity and wilting point on a volumetric basis and a flattening of the water retentivity curves. However, no simple effects of compaction on available water capacity were observed. Changes in PSS, aeration porosity and water retention following compaction allowed the definition of a single parameter, the non-limiting water range (NLWR), to describe more precisely the changes taking place in the air-soil-water matrix following compaction. "Compaction envelopes" were constructed to illustrate these complex inter-relationships and to relate changes in NLWR to compactive effort and relative bulk density. The use of NLWR is recommended as a sensitive parameter for assessing compaction risk of forestry soils.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF SYMBOLS AND ABBREVIATIONS

AWC	=	available water capacity (mm m^{-1})
CAP	=	critical aeration porosity
CPR	=	critical penetration resistance for root growth
CWC	=	critical water content (for maximum bulk density determination)
CWC_{max}	=	critical water content for maximum compressibility
ECEC	=	effective cation exchange capacity (sum of exchangeable bases and exchangeable acidity)
FC	=	field capacity
GMD	=	geometric mean diameter (mm)
GSDEV	=	geometric standard deviation
ICFR	=	Institute for Commercial Forestry Research
MBD	=	maximum bulk density (Mg m^{-3})
NLWR	=	non-limiting water range (mm m^{-1})
P_n	=	normal point resistance (stress on the basal surface of the probe)
P_r	=	total point resistance of a probe
PSS	=	penetrometer soil strength (kPa)
RAW	=	readily available water (mm m^{-1})
RBD	=	relative bulk density (bulk density as a fraction of maximum bullk density)
RSME	=	root mean square error
$RSME_u$	=	unsystematic root mean square error (random)
$RSME_s$	=	systematic root mean square error (bias)
VCC	=	virgin compression curve
VCL	=	virgin compression line
WRC	=	water retentivity curve (plot of water content versus matric potential)
WP	=	wilting point (usually the water content at a matric potential of -1500 kPa)
WPD	=	water-pressure-density (diagram)
WRI	=	water release index (mm m^{-1})
ρ_b	=	bulk density (Mg m^{-3})
ϕ	=	porosity (m^3 m^{-3})
θ_v	=	volumetric water content (m m^{-3})
θ_m	=	mass water content (kg kg^{-1})
ψ_m	=	matric potential (kPa)
σ_r	=	residual pressure (kPa)
σ	=	applied pressure (kPa)
α	=	the included semi-angle of the cone
δ	=	the coefficient of soil-metal friction
ψ_m	=	matric potential

In the Gupta and Larson (1982) model (Equation 2.4)

σ_k	=	reference applied pressure (constant)
S_k	=	reference degree of saturation (constant)
S_1	=	degree of saturation
ρ_k	=	bulk density (Mg m^{-3}) at a S_k and σ_k
Δ_t	=	slope of the relationship between ρ_b and S_1 at a known applied pressure, σ_k

In the compaction model (Equation 2.5)

a	=	a constant describing the relative importance of water content in the compaction process
θ_{mr}	=	residual water content (kg kg^{-1})
σ_r	=	residual pressure (kPa)
σ	=	applied pressure (kPa)
ρ_{bk}	=	bulk density constant in the compaction model (Mg m^{-3})
C_{mod}	=	average compression index in the compaction model
C_{max}	=	maximum compression index

"The real voyage of discovery consists not in seeing new landscapes, but in having new eyes".

Marcel Proust (1871 - 1922)

CHAPTER 1

INTRODUCTION

1.1 Soil compaction and forestry: An overview

Soil compaction is a problem of worldwide concern. Over twenty-five years ago it was estimated that soil compaction was responsible for annual losses of over $1 billion in the United States alone (Gill, 1971). Although the exact economic impact of soil compaction is difficult to ascertain there is overwhelming evidence that soil compaction may induce considerable losses in site productivity in agriculture (Raghavan *et al.*, 1989) and to a lesser extent in forestry (Greacen and Sands, 1980).

Soil physical quality affects the ability of a soil to act as a medium for the transport and supply of water and nutrients to tree roots. Maintainence of soil physical quality underpins the concept of sustainable timber and crop production. In commercial forestry, concern has been expressed that the widespread use of heavy wheeled and tracked vehicles during timber extraction, exacerbated by shortening rotation lengths, may result in a considerable decline in future site productivity (Greacen and Sands, 1980). Impacts due to harvesting operations may include soil compaction, destruction of surface soil structure, nutrient decline through erosion or biomass removals and increased sediment yield as a result of erosion (Moffat, 1991). However, only in the last ten years has attention been drawn to the potential impacts of timber extraction and intensive soil management carried out during commercial forestry operations in South Africa (Grey and Jacobs, 1987).

Soil compaction is not always harmful and to separate harmful from beneficial effects of compaction, Gupta and Allmaras (1987) suggested the use of the term *excessive compaction*. This may be caused by repeated vehicle passes and heavy axle loads or working when the soil is very wet. It is likely that excessive compaction may seriously harm the environment and lead to potential declines in site and stand productivity. As South African forestry practice dictates that harvesting and site preparation take place all year round, even during the wet season, it is likely that appreciable site damage and soil compaction is occurring which could seriously reduce stand productivity (Lockaby and Vidrine, 1984; Grey and Jacobs, 1987). It has been reported that a single clear-felling operation can severely compact between 30 and 80% of a plantation compartment

(Dickerson, 1976; Murphy, 1984; Froehlich *et al.*, 1981; Smith, 1992a).

The degree and type of soil compaction in forest plantations is also central to decisions regarding site preparation options during re-establishment. Corrective measures to alleviate compacted soils may incur considerable expense. Furthermore, amelioration of compaction in forests by tillage is made difficult by the presence of large stumps and roots (Greacen and Sands, 1980). During regeneration of plantations, good planting holes are extremely difficult to establish in compacted soils and may result in a poor soil:root contact and high mortality rates (Smith and Van Huyssteen, 1992). Moehring and Rawls (1970) reported that compaction reduced survival of trees in replanted areas by as much as 57%. When planted in compacted soils, young seedlings are more susceptible to water stress, nitrogen deficiencies (Torbert and Wood, 1992) and soil borne pests and diseases. Since most of our commercial plantations occur on highly weathered non-swelling kaolinitic soils and without the benefit of freeze-thaw cycles, compaction may persist for decades (Froehlich, 1979; Murphy, 1984; Froehlich and McNabb, 1983; Jakobsen, 1983).

Since compaction results in changes in soil structure it is accompanied by alterations in pore geometry (Gupta *et al.*, 1989), water retention properties of soils (Larson *et al.*, 1980; Ohu *et al.*, 1985; Katou *et al.*, 1987), infiltration rates (Akram and Kemper, 1979) and aeration status of soils (Asady and Smucker, 1989; Voorhees *et al.*, 1975). Because of these changes in soil physical properties, soil compaction has been recognized as a problem affecting timber yield, soil erodibility, surface runoff and sediment yield (Moffat, 1991).

Although an introduction and literature review are presented at the beginning of each chapter it is appropriate at this stage to direct the reader to several benchmark papers which provide an excellent background regarding the various facets of soil compaction. The basic compaction process has been described in detail by Harris (1971); the effects of compaction by harvesting equipment on forest soils and forest site productivity by Greacen and Sands (1980); a general review of compaction by agricultural vehicles by Soane (1983); models to assess the relative compaction susceptibility of soils by Gupta and Allmaras (1987); criteria by which to assess the significance of compaction on yield by Voorhees (1991); and compaction affecting tree growth in an urban environment by Jim (1993).

1.2 Background to current research

A great deal of uncertainty prevails concerning the effects of soil compaction on site productivity of commercial forests in South Africa and overseas. This is due in part to the lack of long term growth studies, the complicating effects of previous management operations in retrospective studies (Burger and Powers, 1991), and the modifying effects of residual tree roots from previous rotations (Nambiar and Sands, 1992). Moreover, past recommendations on identification and management of sensitive forestry soils in South Africa (Grey *et al.*, 1987) have depended to a large extent on the extrapolation of information from studies elsewhere in South Africa carried out under very different environmental and land use conditions. These include studies made on, for example, cultivated agricultural soils low in organic carbon (van der Watt, 1969), fine and medium sandy loam soils of the southern and Western Cape (Moolman, 1981), irrigated sandy soils from the Vaalharts Irrigation Scheme (Bennie and Burger, 1988), and on the distinctive soils of the south western Cape viticulture region with its mediterranean climate (Van Huyssteen, 1989).

In view of these deficiencies in knowledge, a compaction research programme was established at the Institute for Commercial Forestry Research (ICFR) in 1991. The principal objective of the programme was to examine the effects of current forestry practices on soil compaction and forest site productivity. The research consisted of two phases comprising (i) identification of soils and areas likely to be at most risk from excessive compaction, i.e. a compaction risk assessment, and (ii) assessment of the impact of timber extraction operations on soil compaction and subsequent tree growth by establishing long term field trials lasting the full rotation length of a timber stand. This thesis provides a detailed report on the progress made to date in the first phase of the work. The strategy adopted had three broad objectives:

* To provide a description of forestry soil behaviour under conditions of varying applied pressures and water contents.

* To establish relationships between soil properties and compaction susceptibility.

* To measure the effects of soil compaction on parameters of soil physical quality.

In this way a logical framework for evaluating the likely effects of soil compaction on forestry site productivity for a wide range of forestry soils could be established. With the acquisition of a fully fledged geographic information system (GIS) at the ICFR this approach allowed for the optimal location of future compaction field trials and an appraisal of the applicability, in terms of geographical extent, of existing trials. Given the increasing number of soil survey maps available to forest managers and planners it was also becoming increasingly important to establish relationships between soil survey data and measures of site sensitivity such as compaction risk. More importantly it was anticipated that addressing the three objectives outlined above would enable identification of gaps in the relational information being collected in the field on a regular basis.

1.3 Thesis structure

To assist the reader an outline is given of the layout of the thesis and the manner in which each of the three principal objectives above were addressed.

Chapters 2 and 3 deal with the procedures for estimating the compaction susceptibility and compaction risk of forestry soils. A description of soil behaviour is given in Chapter 2. This was assessed for a wide range of forestry soils sampled from over 26 locations in the principal timber growing regions of South Africa. The soils were subjected to uniaxial compression for a wide range of applied pressures at a number of water contents corresponding from air-dryness to field capacity. A model was developed which described changes in the compaction status of forestry soils related to applied pressure and water content. The model also allowed an appraisal of the relative importance of water content, compactive effort and soil properties influencing the compaction process. Direct and traditional measures of compaction susceptibility, that is, compressibility and compactibility, were determined in Chapter 3 for all the soils in the study. Critical water contents for compactibility and compressibility were also established. These indices of compaction susceptibility and a range of soil physical and chemical properties were subject to linear and multiple regression to elucidate correlative relationships.

A principal objective of this research was to assess selected aspects of changes in soil physical quality brought about by compaction, and these are dealt with in Chapters 4 and 5. It was anticipated that measuring changes in soil physical quality which directly influence rooting conditions of a soil, and combining these results with the information in Chapters 2 and 3, would provide an additional basis for estimating compaction risk. The suitability of the physical environment for root growth is a function of complex interactions involving soil strength and the ability of the soil to supply air and water to plant roots. Thus, the effect of soil compaction on soil strength was measured in this study by penetrometer soil strength (PSS) and is dealt with in Chapter 4. Relationships between PSS and compaction level were established for all soils in the study by measuring PSS on both pre-wet and tension dried laboratory prepared soil cores for a range of bulk densities and water contents. Models relating PSS to bulk density and water content were developed. An attempt was also made to develop an inclusive model which took into account the effect of soil properties on the relationship between compaction and PSS.

In Chapter 5 an approach to integrate all the changes brought about by compaction by determining the effect of compaction on the non-limiting water range (NLWR) (Letey, 1985) was adopted. The effect of soil compaction on critical growth limiting parameters, i.e. field capacity, wilting point and aeration porosity, was examined for a range of selected forestry soils. By superimposing critical parameters on the W-P-D diagrams established in Chapter 2, the NLWR was calculated for a wide range of forestry soils. Critical parameters chosen included field capacity, wilting point, critical aeration porosity and the PSS-bulk density-water content relationship established in Chapter 3. To gain a better understanding of the effect of compaction on growth limiting factors, the effects of relative bulk density (RBD) and compactive effort (applied pressure) on the NLWR were evaluated for a wide range of forestry soils. As a study of the effects of compaction on water retention characteristics of forestry soils was also made, it was possible to compare NLWR with standard measures of available water capacity.

1.4 Soil compaction terminology

A number of terms and definitions are frequently used in the discussions in this thesis. These are summarised below.

Soil compaction refers to the compression of soils under unsaturated conditions, during which the density of the soil body increases and there is a simultaneous reduction in fractional air volume (Gupta *et al.*, 1989). The degree of compactness is essentially a soil physical condition described by certain state parameters, e.g. void ratio, porosity and bulk density (Harris, 1971). When attached to the word "soil" the term "compacted" is the subject of considerable misuse as not all soil compaction is harmful. Gupta and Allmaras (1987) have emphasised the need to differentiate beneficial compaction from harmful or *excessive compaction.*

Compression refers to a process describing the decrease in soil volume under an externally applied pressure. *Compressibility* refers to the ease with which a soil decreases in volume when subjected to an applied pressure and should not be confused with *compactibility* which refers to the maximum density a soil can achieve by a specified amount of energy (Bradford and Gupta, 1986).

Hardsetting, which describes soils which set to a hard, structureless mass during drying, involves slumping which is a process of compaction without application of an external load (Mullins *et al.*, 1989). In papers which report soil compaction in cultivated and irrigated regions it is often difficult to separate the effects of topsoil structural collapse from externally applied pressures. This is of great practical importance since measures to reduce the area impacted by machinery will have little influence on the compaction problem if the tillage system stays the same (Mullins *et al.*, 1989). It is generally assumed that in the absence of annual tillage operations together with the higher organic matter contents of forestry soils, that most compaction in forestry soils is due to externally applied loads. Instances of hardsetting soils in forestry have been noted to date in former agricultural lands (Smith and Van Huyssteen, 1992) and on specific parent materials, e.g. soils derived from Dwyka tillites and some eastern Transvaal granites.

CHAPTER 2

UNIAXIAL COMPACTION OF FORESTRY SOILS AS AFFECTED BY APPLIED PRESSURE, WATER CONTENT AND SOIL TYPE

2.1 INTRODUCTION

2.1.1 Overview

A number of factors directly influence the compaction process, the most important of which are the surface pressure applied by machinery, the soil water content at time of compaction and soil properties (Akram and Kemper, 1979; Amir *et al.*, 1976). This information is important when developing strategies to manage soil compaction in plantations for a wide range of forestry soils. Studies regarding the effects of various harvesting machinery on soil properties have been made in timber plantations in South Africa (Hattingh, 1990), Australia (Jakobsen and Greacen, 1985; Incerti *et al.*, 1987) and the United States (Dickerson, 1976). However, it is often extremely difficult to extrapolate from these studies to other soil types as detailed soil descriptions and information on compression behaviour are lacking. Even in agriculture where a substantial research effort has been focused on soil compaction, Bradford and Gupta (1986) acknowledged that data in the literature on the compressibility of agricultural soils are limited. Information on compressibility of forestry soils is even more scarce.

2.1.2 Modelling compaction behaviour

Most efforts to describe laboratory compaction have been aimed at developing mathematical equations which characterise stress-compaction relationships in a small sample. Soehne (1958) expressed the relationship between porosity and applied pressure at a given soil water content as:

$$\phi = k - C \ln\sigma \qquad [2.1]$$

where ϕ is the porosity, σ is the pressure in bars, k is a constant and C is the compression index which is the slope of the linear portion of the relationship between porosity or bulk density and the logarithm of applied pressure. This straight line is often termed the virgin compression line or VCL (Figure 2.1). The overall relationship between bulk density and the logarithm of applied pressure is termed the virgin compression curve (VCC). The bulk density will continue to increase until the maximum bulk density is reached and thus equation 2.1 does not apply at very high stresses. If the soil has a previous compaction history and a further stress is applied, the bulk density - applied pressure relationship will continue along a line with a slight slope until it joins the VCC. This is termed secondary compression and is of great practical significance as it indicates that there is very little change in bulk density for increasing applied pressure until the secondary compression line joins the VCL.

The applied pressure required for secondary compression has been termed residual pressure by Amir *et al.* (1976) who defined it as the pressure which, when added to the applied pressure, results in residual compaction, i.e. the difference between the calculated porosity for virgin conditions and the observed porosity of the field soil with a history of compression. The influence of residual pressure on measured porosity decreases with increasing applied pressure.

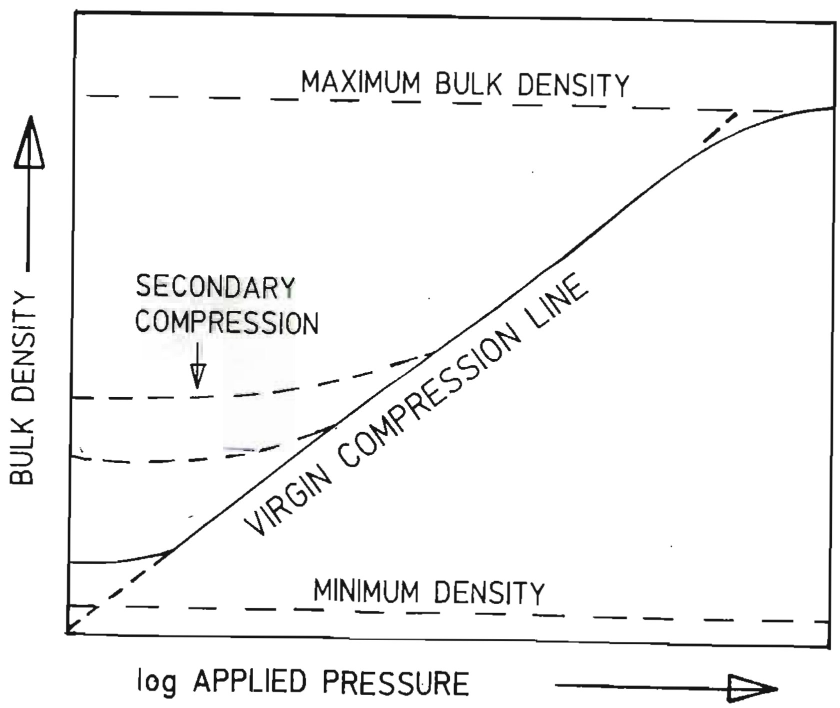


Figure 2.1: Diagram illustrating idealised compression curves.

By analysing previously published results, Amir *et al*. (1976) showed the existence of a combined relationship between porosity, applied pressure and soil water content when the soil water content was between 0.4 and 0.9 of saturation:

$$\phi = k - a \ln(\sigma_r - \sigma) - b \ln\theta_v \qquad [2.2]$$

where *k*, *a* and *b* are constants depending upon soil properties, ϕ is the porosity (%), σ is the applied pressure in psi, θ_v the volumetric water content (%) and σ_r is the residual pressure in psi, that is the pressure which, when added to the applied pressure, results in residual compaction. For virgin soils $\sigma_r = 0$ and the equation above may be restated as:

$$\phi = k - a \ln\sigma - b \ln\theta_v \qquad [2.3]$$

Amir *et al.* (1976) suggested that these equations allowed the prediction of the degree of soil compaction as a function of water content and applied pressure.

Larson *et al.* (1980) determined the relationship between bulk density and applied pressure for a range of agricultural soils and found that compression curves over the range of applied pressures from 100 to 1000 kPa were approximately parallel for a range of water contents corresponding to initial pore water pressures from - 5 kPa to - 70 kPa. The compression curves were described by the relationship:

$$\rho_b = [\rho_k + \Delta_t(S_1 - S_k)] + C \log(\sigma/\sigma_k) \qquad [2.4]$$

where ρ_b is bulk density (Mg m^{-3}), ρ_k is the bulk density (Mg m^{-3}) at a reference degree of water saturation S_k and a reference applied pressure σ_k, σ is the applied pressure (kPa), Δ_t is the slope of the relationship between bulk density ρ_b and degree of water saturation at a known applied pressure σ_k, and S_1 is the required degree of saturation. It is evident that the parameter S_1 is in fact a measure of the sensitivity of the soil to compaction with increasing water content. Although Gupta and Larson (1982) presented equations relating both S_1 and ρ_k to soil texture, no physical explanation for these relationships was forthcoming to explain the compaction process further.

2.1.3 The uniaxial compression test

The uniaxial compression test was chosen in this study as a simple, reliable method which can quantify meaningful differences in forestry soil behaviour under conditions of varying applied pressure and changing water content. From this point of view the uniaxial compression test has proven to be a valuable tool in compaction research (Koolen, 1974; Larson *et al.*, 1980; O'Sullivan, 1992). Koolen (1974) concluded that, providing friction influences of the cell wall are limited, the result of a uniaxial compression test is independent of sample dimensions and as such can be considered to measure a fundamental soil property, i.e. the relationship between porosity or bulk density and applied pressure. In spite of the fact that lateral confining stresses cannot be controlled there is general agreement that as compaction is mainly a function of the principal vertical stress, the uniaxial test provides an adequate simulation of compaction caused by field traffic (Koolen and Vaandrager, 1984; Davidowski and Lerink, 1990; O'Sullivan, 1992).

The status of soil compaction research was outlined recently in a paper by Schafer *et al.* (1992) who emphasised the need for the development of models to describe compaction behaviour from an engineering mechanics point of view. Unfortunately, these models are not readily applicable to agricultural or forestry situations due their tedious and time consuming nature. In a subject such as soil physics where more and more effort is being concentrated on refining rather than applying existing methodologies, it is not surprising that land use planners and decision makers are still faced with a lack of detailed soil physical information on which decisions can be based. This situation has been compounded by the pedologists who have provided a soil classification which presents in ever increasing detail a large number of profile characteristics which have little or no bearing on the management of the soil. The approach taken in this chapter was to describe and compare the compaction behaviour of typical South African forestry soils as affected by a wide range of water contents and applied pressures using a simple uniaxial compression technique. In particular, and in order to quantitatively characterise this behaviour, an attempt was made to fit the data to an appropriate model and to make a practical interpretation of the results for forestry management.

2.2 MATERIALS AND METHODS

2.2.1 Selection and sampling of soils

Thirty-five soils (twenty six topsoils and nine subsoils) covering a wide range of soil textures and organic carbon contents were used in this investigation. The soils were selected to cover a broad range of geological and climatic conditions prevalent throughout the main timber growing areas in South Africa. As such, soils were sampled from Elliot in the northeastern Cape to Graskop in the eastern Transvaal (see Figure 2.2). Bulk soil samples were taken from freshly cut faces in open pits. At the same time the soil profiles were described and classified according to soil form and family (Soil Classification Working Group, 1991) and Soil Taxonomy (Soil Survey Staff, 1990). Additional samples were taken for physical and chemical analysis. Full profile descriptions, site information and soil physical and chemical properties are given in Appendix 1.

2.2.2 Analytical methods

Although analytical procedures are given in detail in Appendix 2 they will be briefly outlined here so that the reader is acquainted with the basic methodology of the chemical and physical measurements.

Soil texture was described in terms of the percentage of clay (< 0.002 mm), fine silt (0.002 - 0.02 mm), coarse silt (0.02 - 0.05 mm), fine sand (0.05 - 0.25 mm), medium sand (0.25 - 0.50 mm) and coarse sand (0.50 - 2.00 mm). This classification of particle size distribution was in accordance with the Soil Classification Working Group (1991) except that the term fine sand will be used from now on to describe fine sand and very fine sand. Soil samples were pre-treated with hydrogen peroxide (30% v/v) and the size fractions were determined by the pipette method (Day, 1965) after treatment with calgon (sodium hexametaphosphate and sodium carbonate) and ultrasound.

Organic carbon was determined by both Walkley-Black (WB) and loss-on-ignition (LOI) methods. Walkley Black organic carbon was the readily oxidized organic carbon fraction determined by the wet oxidation of organic matter using potassium dichromate/sulphuric acid

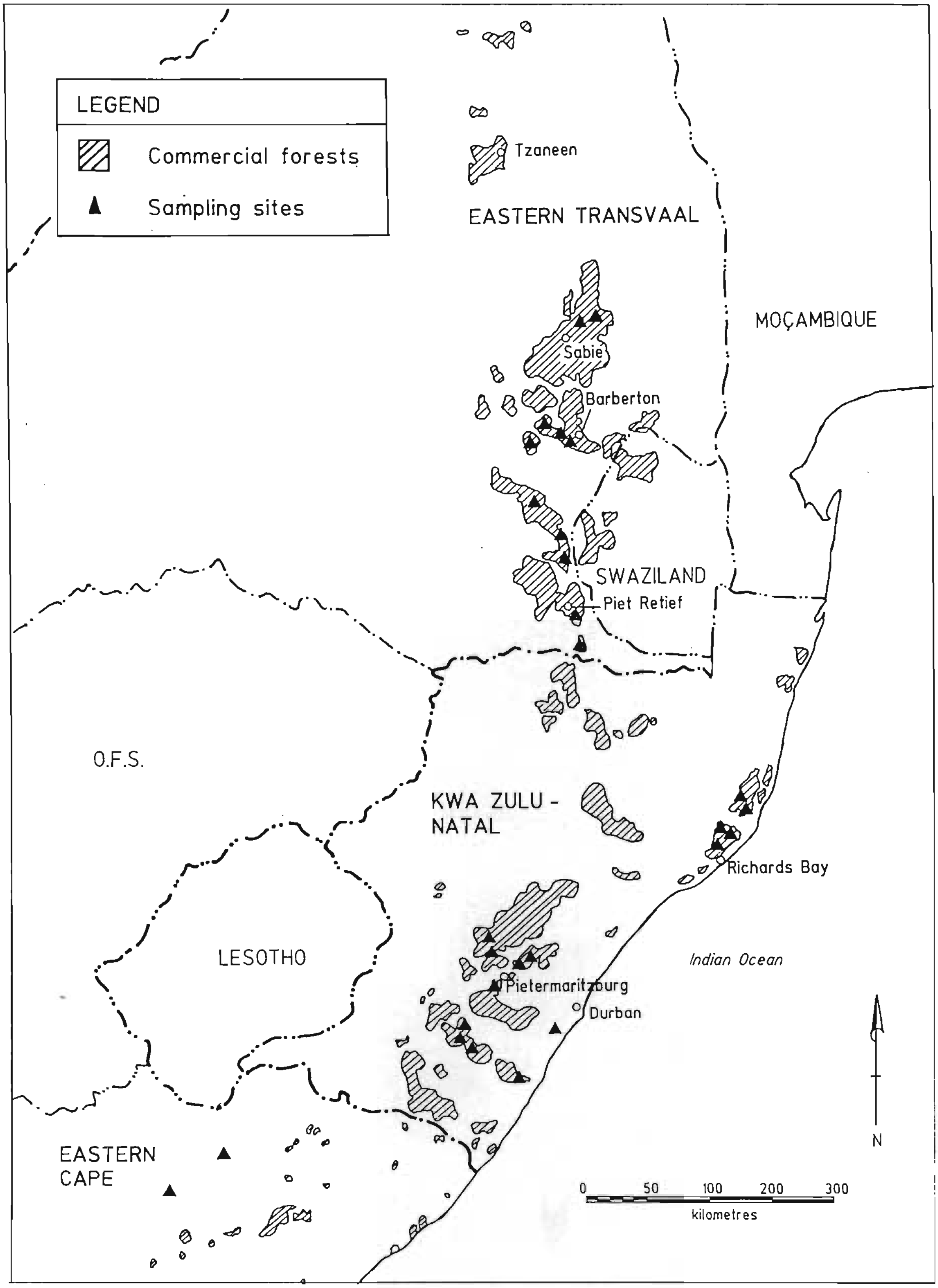


Figure 2.2: Scope of the study: geographical location of sampling sites and principal commercial timber growing areas in the summer rainfall region of South Africa.

(Walkley, 1947). Organic carbon was also estimated from loss-on-ignition (LOI). The loss in mass after ignition at 450°C was expressed as a percentage of oven dry (105°C) soil mass. This figure was then multiplied by a factor of 0.284 to estimate organic carbon according to Donkin (1991).

Exchangeable basic cations, Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} were determined by exchange using 1M pH7 ammonium acetate and subjecting the leachate to atomic absorption/flame emission spectrophotometry.

Exchangeable acidity (Al^{3+} and H^{+}) was determined using unbuffered 1M potassium chloride and titrating against standardised sodium hydroxide solution.

Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable basic and acidic cations and expressed in $cmol_c\ kg^{-1}$.

Soil acidity (pH) was determined in a slurry of 10 g soil in 25 cm^3 deionised H_2O, and in 1M KCl.

2.2.3 Uniaxial compression tests

Field samples of soil were air-dried and passed through a 2 mm sieve. Each soil was wet up to a range of water contents between saturation and wilting point. For each sample approximately 2 kg of the air-dry soil was poured into a plastic tray and brought to the desired moisture content by wetting with an atomiser and thoroughly mixed. The tray was then placed in a plastic bag and the sample was allowed to equilibrate for 48 hours.

After equilibration, soil samples at each water content were placed in open-ended aluminium cores, 77 mm in diameter and 50 mm long*. As the cylinders had no attached base, they were placed on a 5 mm perforated metal base before the soil was added. The cylinders were gently tapped to allow settling of the soil particles. Soil samples in the cylinder were then subject to applied pressures of 0, 100, 200, 400, 600, 800, 1000 and 1400 kPa respectively applied by an hydraulic press consisting of an hydraulic ram connected to a piston (Koolen, 1974). A hand pump was used to bring the oil in the system to a pressure which applied the required load on the soil via the piston and ram (see Figure 2.3). This pressure was maintained for a few seconds and then released. The samples were allowed to rebound before final heights were measured. Water and air could escape around the piston and through fine perforations in the base plate. The depression in the soil surface from the rim of the cylinder was measured at three points around the core using a Vernier scale. These measurements were used later to calculate bulk density.

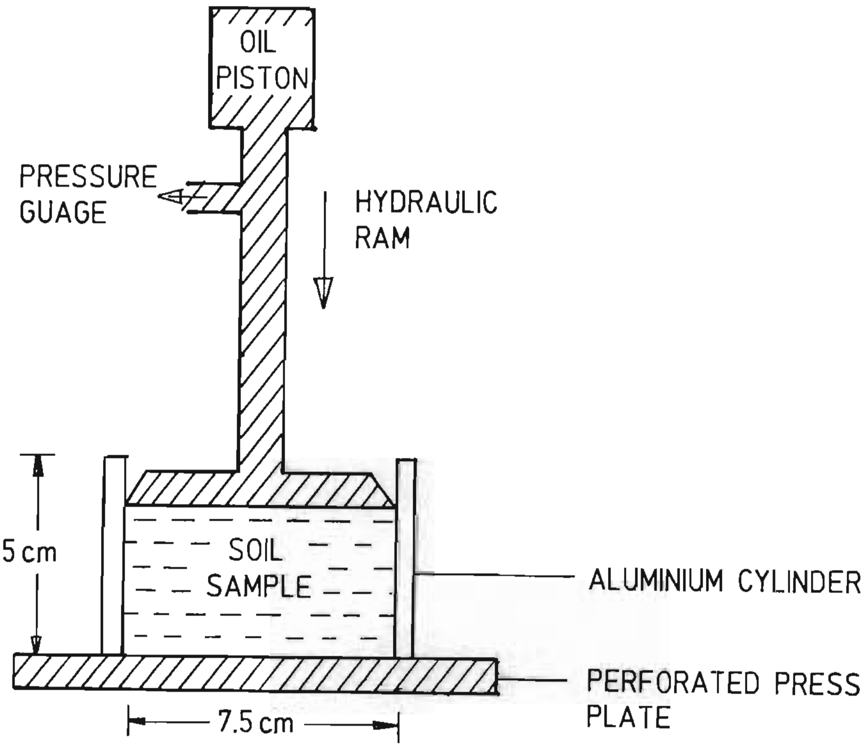


Figure 2.3: Uniaxial compression apparatus.

*The interfering influence of the friction forces between the cell wall and the cylinder can be minimised by choosing suitable cell dimensions (Koolen, 1974). Theoretically, high D/h ratios, where D = diameter of cell, and h = height of cell, are preferred to minimise friction. However, very high D/h ratios are impractical due to small sample height and the difficulty of measuring change in h accurately. The D/h ratio used in these tests (1.54) was regarded as reasonable in limiting the effects of wall friction and permitting acceptable measurement accuracy.

2.3 RESULTS AND DISCUSSION

Soil identification and site characteristics of the forestry soils used in this study are presented in Table 2.1. Selected physical and chemical properties of the soils are given in Tables 2.2 and 2.3 respectively. A feature of this research was the wide range of soil textures and organic carbon levels in the forestry soils. Clay contents ranged from 8 to 66 % and organic carbon values (WB) from 0.26 to 5.77%. In addition, the general lack of 2:1 clay minerals in all the soils studied was evident from the low ECEC values, which ranged from 0.85 to 12.96 $cmol_c\ kg^{-1}$ soil with 85% of all soils having an ECEC of less than 6.00 $cmol_c\ kg^{-1}$ soil. A feature of Table 2.2 is that most organic carbon values for topsoils as estimated by the loss-on-ignition (LOI) method were lower than those obtained by the Walkely-Black method. This was unexpected but can be explained by apparent limitations in the applicability of the factor established by Donkin (1991). His data set included a higher proportion of soils with high clay contents than in this study. This had the effect of creating a relatively shallow slope for the relationship between WB organic carbon (dependent variable) and LOI, i.e. it produced a relatively low conversion factor. As a result there appears to be an underprediction of organic carbon (LOI) for many soils in this study. It is therefore instructive to note that, with respect to organic carbon (WB), the factor of 0.284 resulted in similar and sometimes higher organic carbon (LOI) values for finely textured topsoil samples in this study, i.e. 4A, 6A & 19A.

Relationships between bulk density/porosity and applied pressure for a range of water contents are presented on the left hand side of Figure 2.4(a - l) using soil water-applied pressure-bulk density diagrams, hereafter referred to as **W-P-D diagrams.** The same data are presented on the right hand side of Figure 2.4(a - l) as semi-log plots of bulk density against applied pressure (compression curves). All the graphs have been plotted at the same scale to enable visual comparison. The lines on the W-P-D diagrams have been drawn as smoothed curves through the data points. For clarity, data points have not been drawn in on the W-P-D diagrams as the same data are represented on the compression curves on the right hand side.

The pertinent features of the W-P-D diagrams are, for a given applied pressure, increasing compaction with increasing water content at relatively low water contents and decreasing compaction as the soil becomes wetter and less compressible due to the pores becoming increasingly filled with water. Relatively level, closely spaced iso-stress lines indicate little change in soil volume across a range of water contents and applied pressures. Widely spaced lines indicate rapid loss in porosity for incremental increases in applied pressure. Steep iso-stress lines demonstrate strong dependence on soil water content at the time of compaction. The compression curves on the right hand side of Figure 2.4(a - l) support the results of Larson *et al*. (1980), showing a shift to the left in the VCC with increasing water content.

Table 2.1: Soil identification and site characteristics of the soils studied

Site No.	Location	Soil Classification: Soil Form and Family*	Soil Classification: Soil Taxonomy**	Topsoil Texture	Parent Material***
NATAL MIDLANDS AND SOUTH COAST					
1	Highflats	Lusiki 1110	Typic Kanhaplustalf	Loam	Dwyka tillite
2	Highflats	Cartref 2100	Typic Haplaquept	Sandy loam	Natal Group sandstone
3	Highflats	Lusiki 2120	Aquic Kanhaplustalf	Loam	Dwyka tillite
4	Pietermaritzburg	Magwa 1200	Ustic Kanhaplohumult	Silty clay	Ecca shale
5	Wartburg	Inanda 1200	Ustic Kandihumult	Sandy clay loam	Natal Group sandstone
6	Shafton	Kranskop 1100	Humic Haplustox	Silty clay	Dolerite
7	Howick	Kranskop 1100	Humic Haplustox	Clay	Dolerite
8	Pietermaritzburg	Inanda 1200	Typic Kanhaplustult	Silty clay loam	Ecca shale
9	Ifafa	Nomanci 2200	Pachic Haplumbrept	Sandy clay loam	Pelitic gneiss/schist
10	Umkomaas	Cartref 2200	Typic Haplaquept	Loam	Dwyka tillite
NATAL - ZULULAND					
11	Kwambonambi	Fernwood 1210	Typic Ustipsamment	Loamy sand	Recent sands
12	Kwambonambi	Fernwood 1220	Alfic Ustipsamment	Loamy sand	Recent sands
13	Kwambonambi	Fernwood 1110	Aquic Ustipsamment	Loamy sand	Recent sands
14	Kwambonambi	Hutton 2100	Typic Kandiustult	Sandy loam	Berea sandstone
15	Kwambonambi	Fernwood 2110	Typic Ustipsamment	Loamy sand	Recent sands
EASTERN TRANSVAAL HIGHVELD					
16	Piet Retief	Nomanci 1200	Lithic Ustochrept	Sandy clay loam	Biotite granite
17	Piet Retief	Hutton 1200	Typic Kandiustult	Sandy clay loam	Biotite granite
18	Amsterdam	Inanda 1200	Typic Kanhaplustult	Sandy clay loam	Leucocratic granite
19	Amsterdam	Kranskop 1100	Humic Xanthic Haplustox	Clay	Diabase
20	Warburton	Clovelly 1100	Lithic Haplustox	Sandy clay loam	Ecca sandstone
21	Lothair	Kranskop 1100	Typic Haplustox	Sandy clay	Granitic gneiss
EASTERN TRANSVAAL ESCARPMENT					
22	Barberton	Hutton 1200	Rhodic Kanhaplustult	Sandy clay loam	Hornblende biotite granite/diabase
23	Barberton	Swartland 1211	Rhodic Kanhaplustalf	Sandy clay loam	Diabase
24	Barberton	Swartland 2111	Typic Kanhaplustalf	Sandy clay loam	Hornblende biotite granite/diabase
25	Graskop	Inanda 1200	Typic Kandihumult	Sandy clay loam	Biotite granite
26	Graskop	Magwa 1100	Humic Xanthic Haplustox	Sandy clay loam	Biotite granite

* Soil Classification Working Group (1991)
** Soil Survey Staff (1990)
*** Taken from various 1:250 000 Geological Series maps, Geological Survey.

Table 2.2: Selected physical properties of the soils studied

Site No. and horizon	Soil form	Soil texture	Particle size distribution (%)						Organic carbon (%)		Cl + Si
			Cl	fi Si	co Si	fi Sa	m Sa	co Sa	LOI	WB	
1A	Lu	Lm	22	22	25	20	7	4	1.88	4.02	69
2A	Cf	SaLm	13	8	9	33	34	3	0.65	1.42	30
2E	Cf	SaLm	11	8	7	25	31	18	0.23	0.32	26
3A	Lu	Lm	24	17	17	25	10	6	1.66	2.37	58
4A	Ma	SiCl	41	19	33	3	1	3	4.03	2.10	93
5A	Ia	SaClLm	30	6	9	23	24	8	1.91	2.15	45
6A	Kp	SiCl	51	17	27	2	1	2	5.25	5.77	95
6B	Kp	Cl	46	10	19	10	2	13	3.97	2.64	75
6B2	Kp	Cl	65	12	11	3	5	4	3.20	1.09	88
7A	Kp	Cl	56	9	12	11	8	4	3.21	4.22	77
8A	Ia	SiClLm	40	15	29	6	3	7	2.36	3.58	84
8B	Ia	Cl	50	14	23	2	1	10	1.27	1.06	87
9A	No	SaClLm	27	8	14	20	15	16	2.38	3.83	49
10A	Cf	Lm	16	18	16	34	13	3	0.61	0.95	50
11A	Fw	LmSa	8	8	2	38	43	2	0.20	0.29	18
12A	Fw	LmSa	8	4	2	37	45	5	0.16	0.26	14
13A	Fw	LmSa	9	3	2	41	39	6	0.23	0.38	14
14A	Hu	SaLm	12	5	4	32	36	11	0.39	0.43	21
15A	Fw	LmSa	9	5	6	41	34	5	0.89	1.65	20
16A	No	SaClLm	24	6	11	19	21	19	1.25	2.36	41
17A	Hu	SaClLm	26	3	7	13	31	20	0.78	1.49	36
17B	Hu	SaClLm	29	3	3	14	29	22	0.84	1.09	35
18A	Ia	SaClLm	28	8	8	31	17	8	1.14	2.42	44
19A	Kp	Cl	66	7	21	4	1	1	4.36	4.13	94
20A	Cv	SaClLm	35	7	9	18	17	14	1.14	1.37	51
20B	Cv	SaClLm	31	7	12	15	16	19	1.02	0.92	50
21A	Kp	SaCl	44	6	9	9	11	21	2.56	4.23	59
21B	Kp	Cl	46	6	10	6	5	27	1.40	1.05	62
22A	Hu	SaClLm	32	2	6	13	24	23	1.13	1.21	40
22B	Hu	Cl	52	2	6	10	13	17	1.38	0.34	60
23A	Sw	SaClLm	34	7	13	18	19	9	1.50	1.57	54
24A	Sw	SaClLm	30	5	12	11	14	28	0.82	1.94	47
24B	Sw	ClLm	38	6	12	10	11	23	0.80	1.46	56
25A	Ia	SaClLm	34	3	8	6	12	37	1.81	2.85	45
26A	Ma	SaClLm	30	3	8	7	18	34	2.85	3.42	41

Table 2.3: Selected chemical properties of the soils studied

Site No. and horizon	Soil form	Soil texture	Exchangeable cations ($cmol_c$ kg^{-1})					ECEC ($cmol_c$ kg^{-1})	pH	
			Na	Ca	Mg	K	Exch. acidity		KCl	H_2O
1A	Lu	Lm	0.27	2.37	2.73	0.40	1.00	6.77	3.95	5.15
2A	Cf	SaLm	0.18	0.38	0.69	1.29	0.97	3.51	3.95	4.85
2E	Cf	SaLm	0.17	0.41	0.47	0.08	0.29	1.42	4.25	5.90
3A	Lu	Lm	0.10	1.06	1.58	0.07	1.23	4.04	3.85	5.05
4A	Ma	SiCl	0.04	0.89	0.56	0.08	4.78	6.38	3.95	4.75
5A	Ia	SaClLm	0.65	1.10	0.57	1.02	0.60	3.94	n.d	n.d
6A	Kp	SiCl	0.16	2.02	1.26	0.20	1.18	4.82	4.45	5.65
6B	Kp	Cl	0.20	0.80	0.96	0.19	0.11	2.26	4.75	5.95
6B2	Kp	Cl	0.13	0.85	0.55	0.08	0.03	1.64	5.15	5.85
7A	Kp	Cl	0.14	0.49	0.78	0.20	1.95	3.56	4.20	4.50
8A	Ia	SiClLm	0.17	5.41	3.30	0.18	0.60	9.66	4.55	5.50
8B	Ia	Cl	0.62	4.51	4.76	0.18	0.20	10.27	4.59	6.10
9A	No	SaClLm	0.24	8.81	3.64	0.16	0.11	12.96	n.d	n.d
10A	Cf	SaLm	0.19	0.69	0.37	0.39	1.37	3.01	3.80	4.30
11A	Fw	LmSa	0.06	0.48	0.20	0.01	0.10	0.85	4.45	5.80
12A	Fw	LmSa	0.05	0.24	0.19	0.25	0.23	0.96	4.00	5.10
13A	Fw	LmSa	0.07	0.67	0.32	0.02	0.10	1.19	4.35	5.50
14A	Hu	SaLm	0.17	0.26	0.51	0.11	0.11	1.16	3.90	5.95
15A	Fw	LmSa	0.25	1.02	0.48	0.07	0.07	1.89	4.10	5.80
16A	No	SaClLm	0.10	2.68	1.33	0.55	0.09	4.75	4.95	6.45
17A	Hu	SaClLm	0.10	1.85	0.38	0.11	0.81	3.25	4.30	5.05
17B	Hu	SaClLm	0.10	1.55	0.36	0.13	1.08	3.22	4.25	5.25
18A	Ia	SaClLm	0.07	0.44	0.38	0.16	1.50	2.55	3.70	4.65
19A	Kp	Cl	0.05	1.50	1.02	0.15	0.95	3.67	4.10	5.65
20A	Cv	SaClLm	0.06	0.19	0.11	0.00	1.40	1.76	3.95	5.70
20B	Cv	SaClLm	0.00	0.17	0.10	0.40	1.12	1.43	4.05	4.30
21A	Kp	Cl	0.16	1.11	0.14	0.27	1.16	2.84	4.15	5.35
21B	Kp	Cl	0.23	1.10	0.08	0.16	0.75	2.32	4.35	6.15
22A	Hu	SaClLm	0.18	0.87	0.16	0.14	0.89	2.24	4.25	5.85
22B	Hu	Cl	0.14	0.55	0.09	0.16	1.75	2.69	4.35	5.65
23A	Sw	SaClLm	0.14	4.79	0.73	0.03	0.05	5.74	5.20	6.50
24A	Sw	SaClLm	0.10	5.84	1.26	0.55	0.13	7.88	5.90	6.40
24B	Sw	ClLm	0.14	0.92	0.22	0.25	0.72	2.25	4.30	5.20
25A	Ia	SaClLm	0.14	0.55	0.23	0.11	0.95	1.98	4.05	5.05
26A	Ma	SaClLm	0.15	0.53	0.12	0.08	1.86	2.74	3.85	4.75

2.3.1 Compression behaviour of forestry soils

In order to gain an insight into the compression behaviour of forestry soils a general discussion on the main characteristics of the W-P-D diagrams will follow. The virgin compression curves on the right of each W-P-D diagram will not be discussed in detail and mainly serve to illustrate the W-P-D relationships from another view. It should be borne in mind that the compression index can be calculated from the VCC being the slope of the straight line portion of these curves, the VCL, which usually occurs between 100 and 1000 kPa. For convenience the results for Natal and Transvaal forestry soils will be discussed separately. Average compression indices (C_{mod}) were calculated for each soil and are presented in Table 2.4. A full explanation of the regression parameters presented in Table 2.4 is given in Section 2.3.2 on modelling compaction behaviour.

2.3.1.1 Natal soils

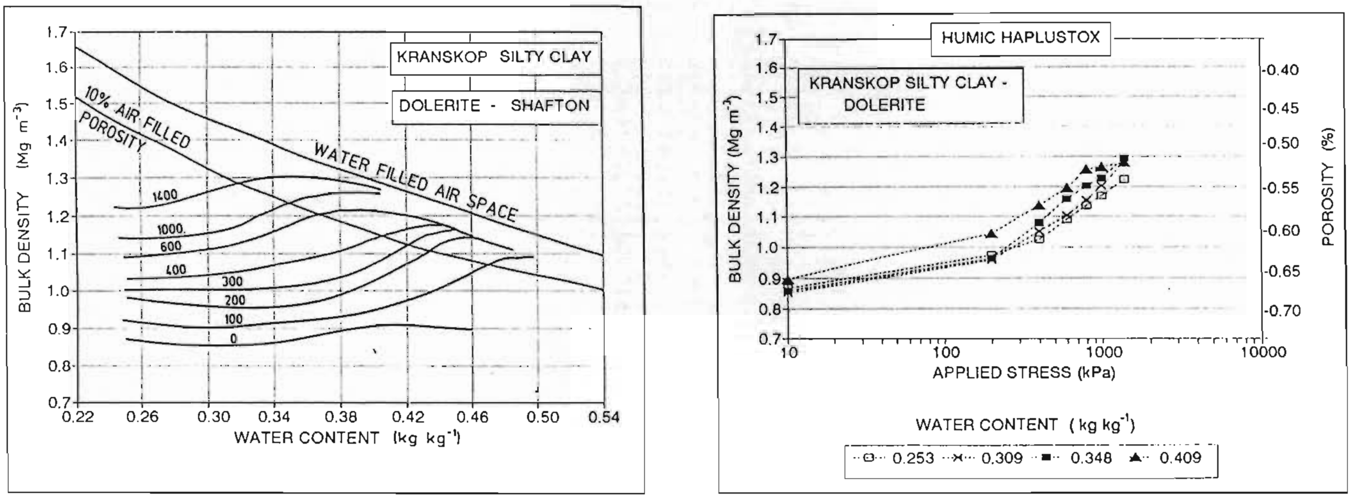
Figures 2.4a and b show the compaction behaviour of a Kranskop silty clay (6A) and Magwa silty clay (4A). The iso-stress lines have a shallow gradient and relatively close spacing across a wide range of water contents, indicating that compaction behaviour is similar for a wide range of water contents. This is in part due to the high clay plus silt content and high organic carbon content for both these soils (Ohu *et al.*, 1985). The Kranskop and Magwa soils had organic carbon (LOI) contents of 5.25 % and 4.03 % respectively (Table 2.2). Although the iso-stress lines have a relatively shallow gradient they are still relatively widely spaced, demonstrating that despite the high organic carbon content the soils are still relatively compressible. This point is confirmed by C_{mod} values of close to 0.318 and 0.337 for the Kranskop (6A) and Magwa (4A) soils respectively (Table 2.4). These results support the conclusion of O'Sullivan (1992) who found that the influence of water content on specific volume was less for soils with greater organic matter contents and that organic matter content had little influence in the relative change of specific volume with changes in applied pressure.

W-P-D diagrams for two Natal forestry soils derived from tillite and sandstone are shown in Figures 2.4c and 2.4d respectively. Both the relatively wide spacing of the iso-stress lines and the moderate C_{mod} values of 0.355 and 0.339 (Table 2.4) for the Lusiki loam (3A) and Inanda sandy clay loam (5A) respectively, indicate that compressibility of these soils is strongly dependent upon water content (widely spaced lines) and that they are only moderately compressible for an increment of applied pressure.

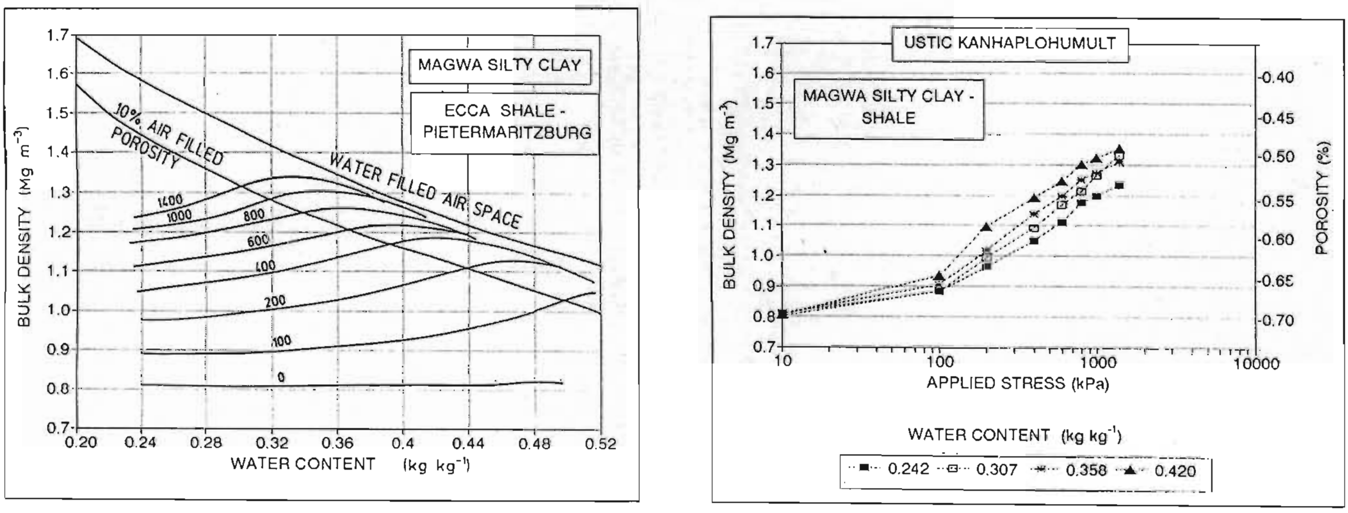
The steepness of the iso-stress lines of both the Inanda sandy clay loam and Cartref loam (Figures 2.4d and e respectively) illustrates a resistance to compaction when dry but susceptibility to compaction when moist to wet. Such behaviour reflects a rapid change in bearing capacity due to large changes in soil strength across a narrow range of water contents which in this case is less than 0.05 (kg kg^{-1}) for the Cartref loam (10A). Such behaviour is typical of hardsetting soils (Mullins *et al.*, 1989). The Cartref loam is only moderately resistant to compression which is borne out by the moderate C_{mod} of 0.363 for this soil (Table 2.4).

The Fernwood loamy sand (13A) exhibits considerable resistance to compression, illustrated by the relatively level and closely spaced iso-stress lines (Figure 2.4f). The C_{mod} for the Fernwood loamy sand is only 0.131 (Table 2.4) demonstrating that for a given incremental load only small increases in compaction are noted. These results are consistent with those of Larson *et al.* (1980) who showed that sandy soils are much less compressible than more finely textured soils. The Fernwood loamy sand achieves higher bulk densities when it is very dry or approaching saturation (Figure 2.4f) but this is a feature of the unique particle rearrangement of sands with changing water content rather than the effect of an applied pressure at intermediate water contents. Akram and Kemper (1979) and Panayiotopolous and Mullins (1985) found that air-dry and nearly saturated sands always packed more closely under a given load than at intermediate water contents. Panayiotopolous and Mullins (1985) suggested this was related to annular bridges being formed between sand particles which act like elastic bonds when the soil is moist but are lost when the soil is saturated or air dry and hence the soil at these two extremes collapses. Thus a sandy soil apparently compacts more when it is saturated or air-dry than at intermediate water contents even though the effect of an increment of applied pressure on bulk density is greater at intermediate water contents. Sandy soils are also more sensitive to compaction by vibration, especially when very wet.

(a) Kranskop form (6A)



(b) Magwa form (4A)



(c) Lusiki form (3A)

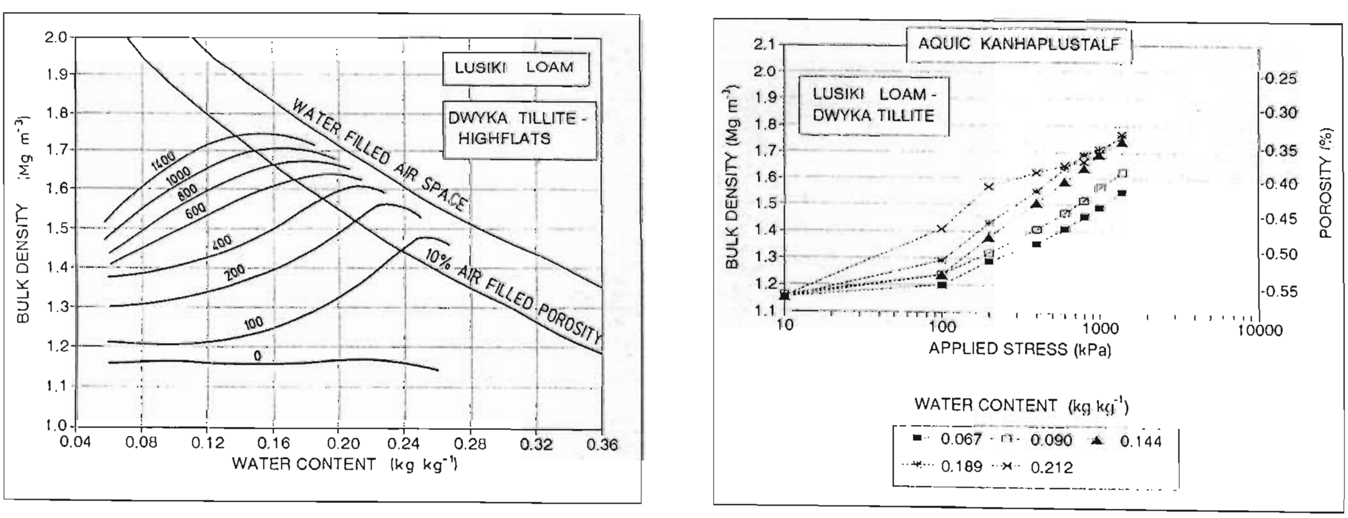
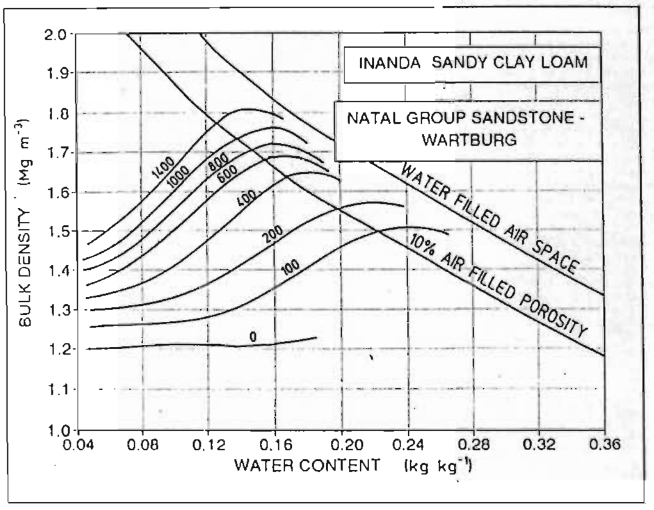
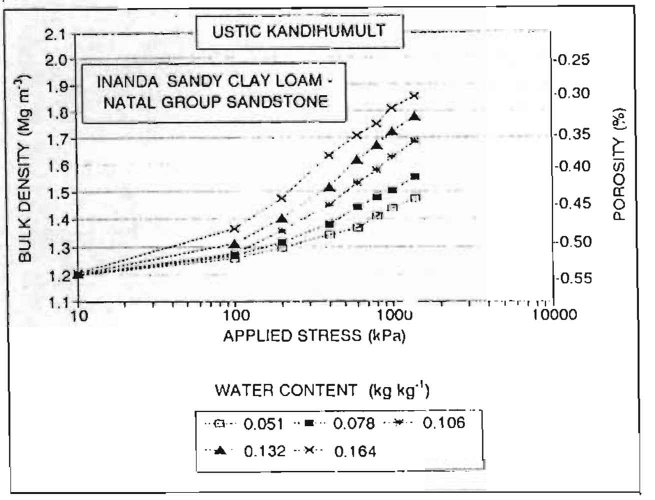


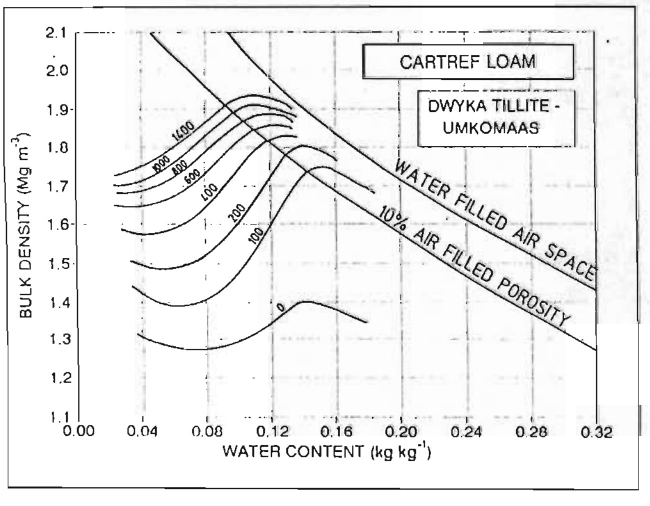
Figure 2.4: W-P-D diagrams (left) and compression curves (right) for selected forestry soils. Iso-stress lines are in kPa.

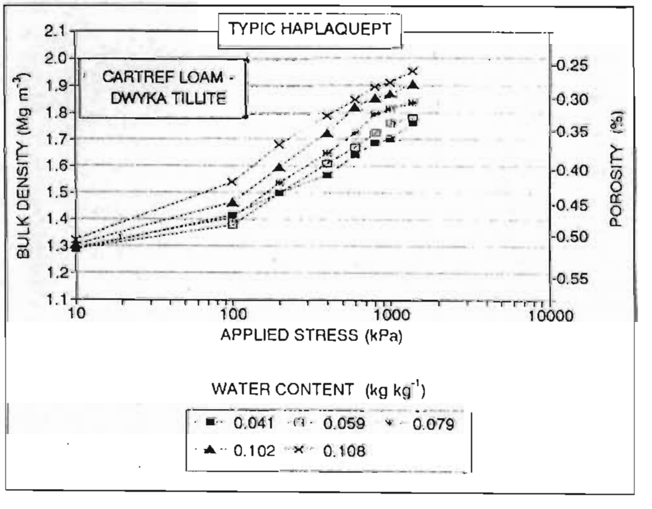
(d) Inanda form (5A)



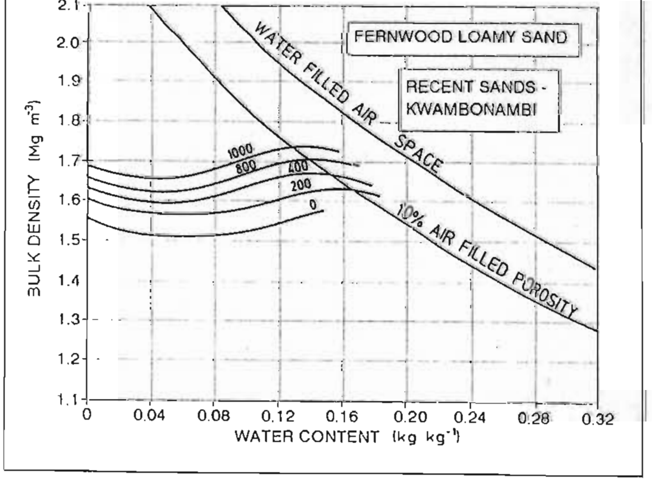


(e) Cartref form (10A)





(f) Fernwood form (13A)



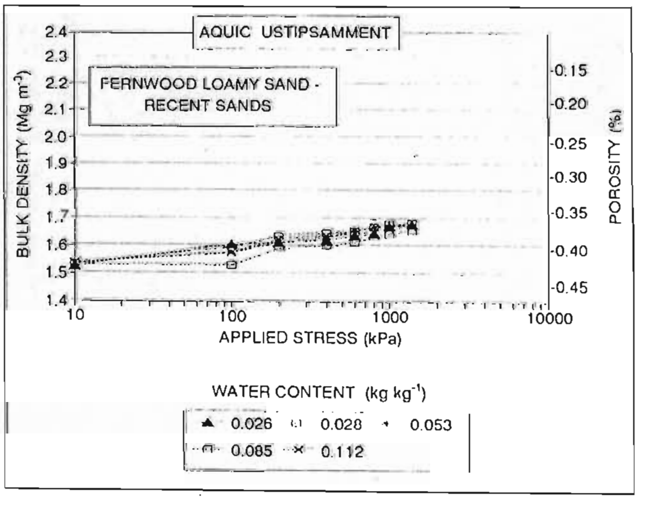
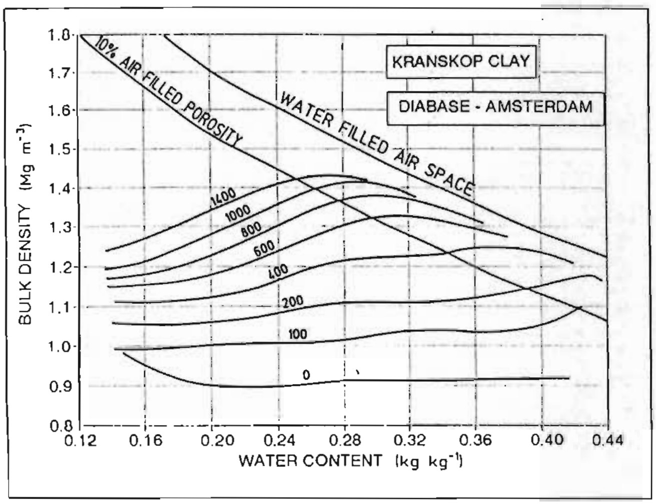
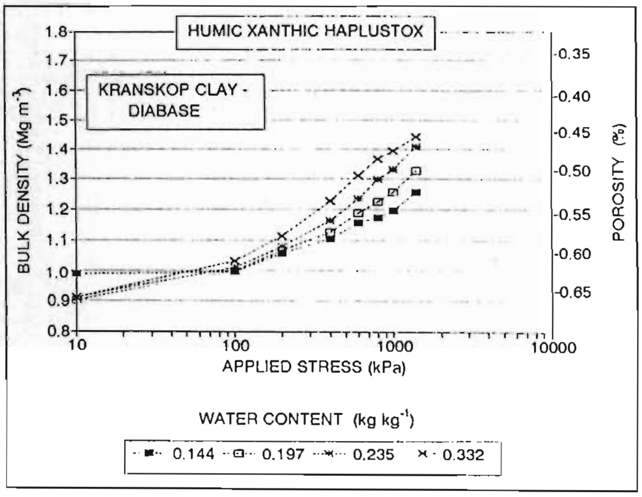


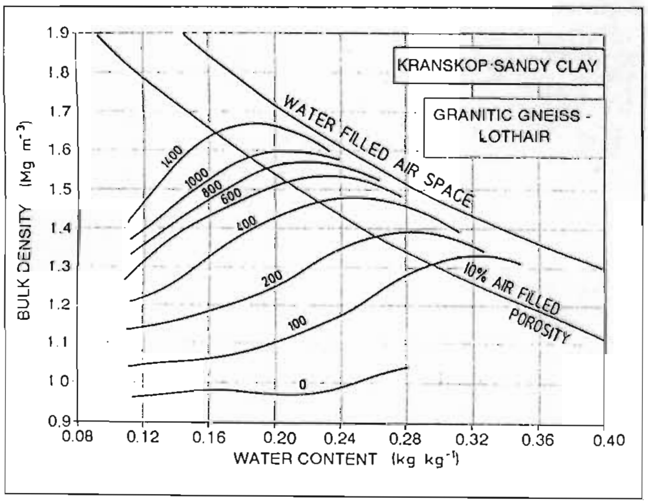
Figure 2.4 (continued)

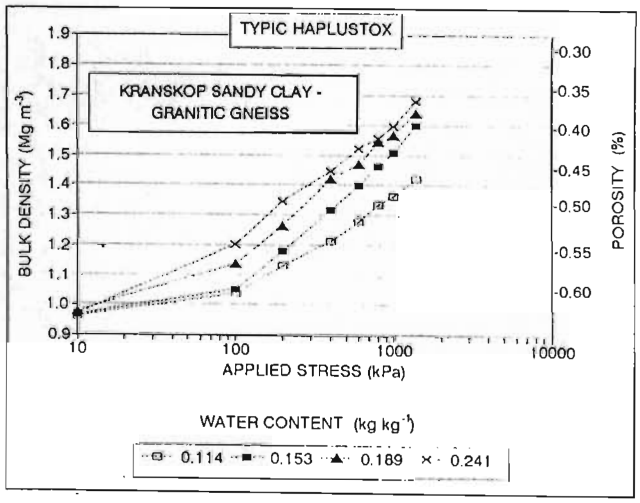
(g) Kranskop form (19A)



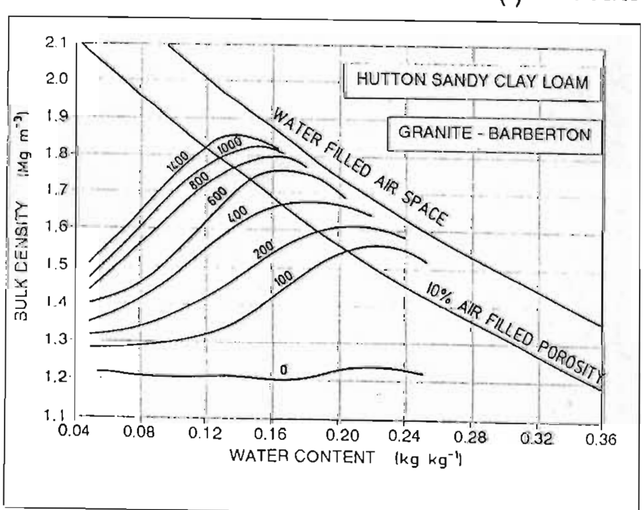


(h) Kranskop form (21A)





(i) Hutton form (22A)



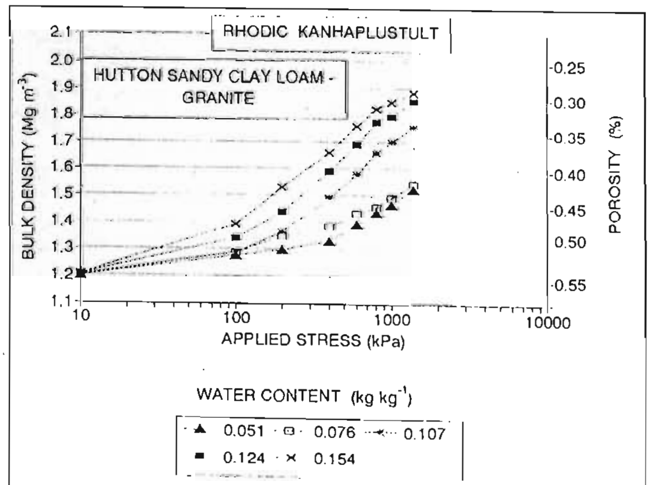
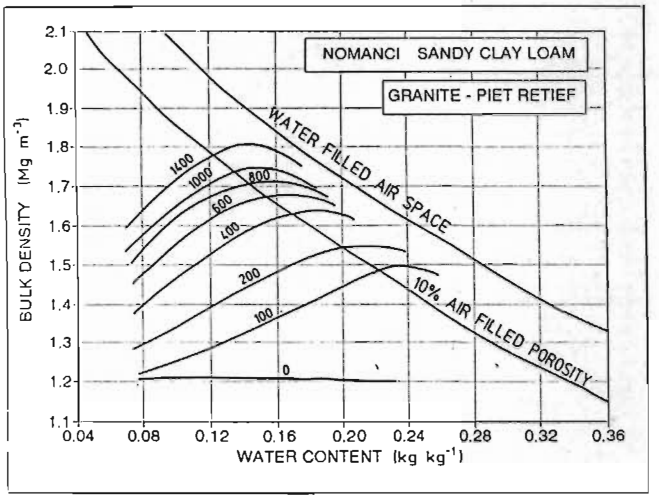
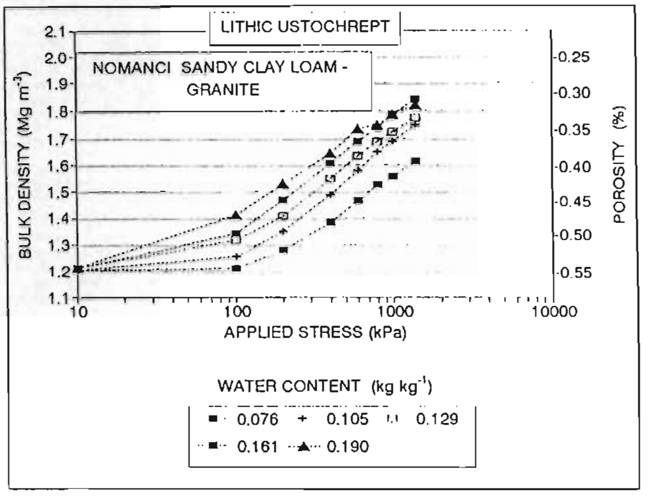


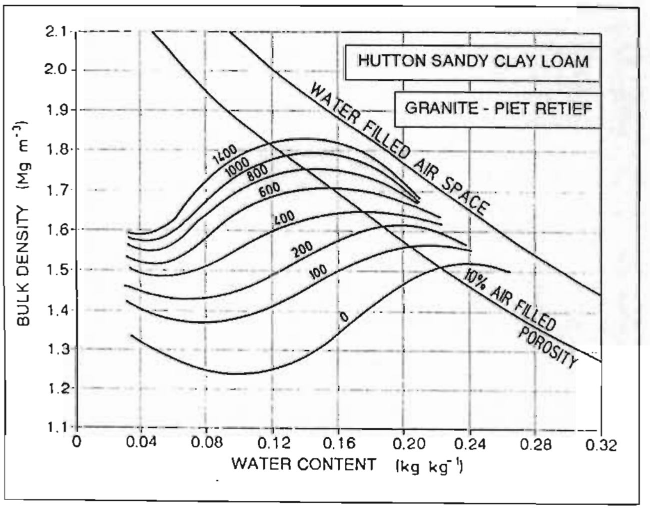
Figure 2.4 (continued)

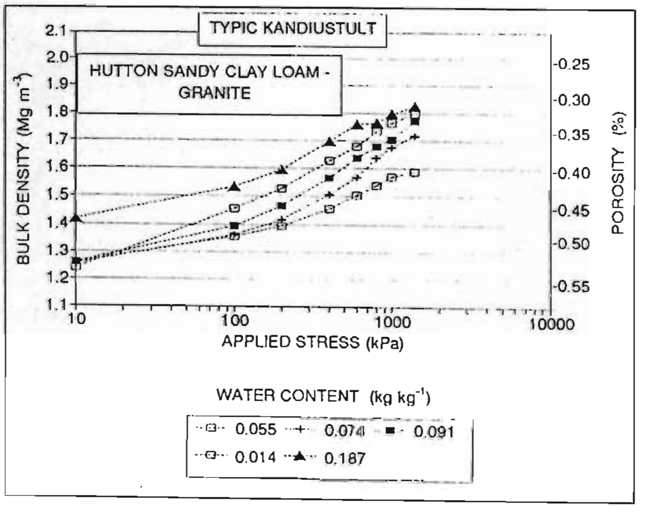
(j) Nomanci form (16A)



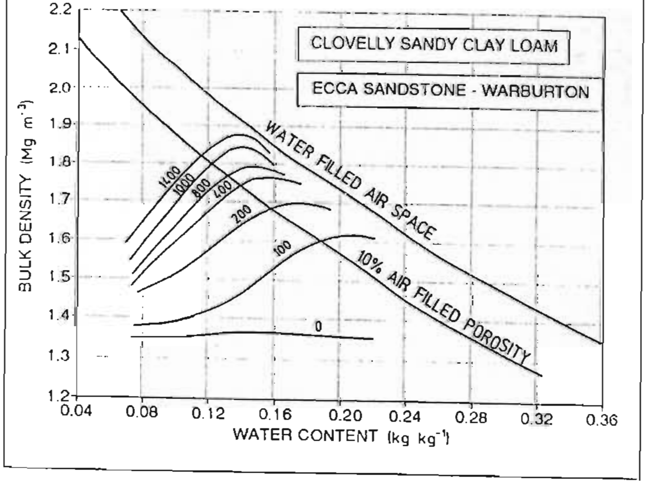


(k) Hutton form (17A)





(l) Clovelly form (20A)



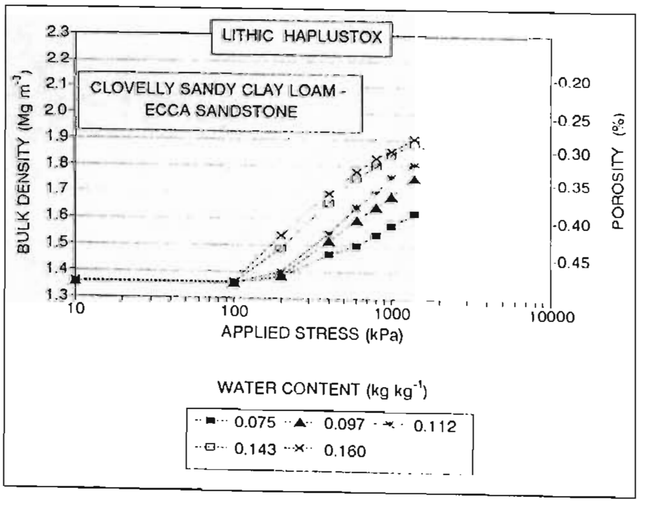


Figure 2.4 (continued)

Table 2.4: Values of the constants and coefficients of Equation 2.5 relating bulk density to applied stress for a range of forestry soils.

Site No. and horizon	No of samples and (df)*	C_{mod}	S.E.E.**	a	S.E.E.**	ρ_{bk}	S.E.E.**	R	Compaction code***
1A	30(27)	0.470	0.015	2.012	0.147	1.043	0.023	0.987	HS
2A	49(46)	0.318	0.008	0.888	0.080	1.331	0.022	0.986	MI
2E	49(46)	0.298	0.014	1.073	0.298	1.436	0.028	0.974	LI
3A	42(39)	0.355	0.015	1.342	0.092	1.174	0.036	0.976	MI
4A	35(32)	0.337	0.015	0.431	0.071	0.877	0.034	0.971	MI
5A	42(39)	0.339	0.016	2.492	0.130	1.137	0.039	0.977	MS
6A	30(27)	0.318	0.026	0.940	0.116	0.835	0.039	0.943	MI
6B	35(32)	0.284	0.016	1.039	0.094	0.898	0.037	0.964	LI
6B2	35(32)	0.216	0.019	1.564	0.135	0.906	0.041	0.954	LS
7A	24(21)	0.309	0.026	0.339	0.102	0.957	0.036	0.936	MI
8A	42(39)	0.415	0.023	0.720	0.132	1.089	0.057	0.948	HI
8B	42(39)	0.516	0.025	2.099	0.315	1.004	0.062	0.964	HS
9A	35(32)	0.446	0.013	2.033	0.116	1.084	0.029	0.989	HS
10A	35(32)	0.363	0.012	2.761	0.181	1.349	0.027	0.986	MS
11A	35(32)	0.092	0.016	-0.217	0.259	1.525	0.035	0.908	LI
12A	35(32)	0.082	0.007	0.153	0.071	1.573	0.016	0.895	LI
13A	35(32)	0.131	0.010	0.085	0.098	1.537	0.023	0.913	LI
14A	30(27)	0.168	0.016	1.728	0.290	1.438	0.024	0.918	LS
15A	60(57)	0.130	0.008	-0.128	0.086	1.479	0.018	0.899	LI
16A	35(32)	0.408	0.012	1.995	0.116	1.185	0.028	0.988	HS
17A	49(46)	0.270	0.012	1.383	0.087	1.316	0.033	0.970	LI
17B	49(46)	0.321	0.023	2.633	0.228	1.259	0.060	0.938	MS
18A	49(46)	0.410	0.010	1.559	0.120	1.047	0.027	0.987	HS
19A	42(39)	0.328	0.017	0.588	0.080	0.932	0.041	0.957	MI
20A	35(32)	0.397	0.019	2.611	0.238	1.230	0.043	0.972	MS
20B	42(39)	0.305	0.022	3.475	0.194	1.176	0.054	0.964	MS
21A	56(53)	0.460	0.018	1.169	0.133	0.997	0.050	0.982	HI
21B	42(39)	0.463	0.014	4.302	0.320	1.178	0.303	0.988	HS
22A	42(39)	0.356	0.021	2.972	0.179	1.144	0.052	0.966	MS
22B	35(32)	0.440	0.032	2.654	0.362	0.987	0.071	0.941	HS
23A	35(32)	0.450	0.024	2.845	0.225	1.085	0.045	0.974	HS
24A	42(39)	0.369	0.020	2.078	0.151	1.249	0.048	0.966	MS
24B	35(32)	0.381	0.023	2.403	0.207	1.169	0.051	0.964	MS
25A	22(19)	0.424	0.026	2.955	0.300	1.074	0.032	0.978	HS
26A	24(21)	0.391	0.061	0.915	0.494	1.154	0.083	0.823	MS

* Degrees of freedom

** Standard error of the estimate

*** Compaction code (see page 27)

2.3.1.2 Transvaal soils

W-P-D diagrams for selected forestry soils in Transvaal are presented in Figure 2.4(g - l). The Kranskop clay (Figure 2.4g) possesses relatively level but widely spaced iso-stress lines, demonstrating that although compaction response to applied pressure is similar across a wide range of moisture contents the soil is moderately compressible. This is illustrated by a C_{mod} value of 0.328 (19A, Table 2.4) for this soil. This compaction behaviour is similar to the Kranskop and Magwa soils from Natal described previously (Figure 2.4a and b) and is related to the high organic carbon and clay content. This soil was similarly derived from a base-rich ultramafic parent material, diabase.

The iso-stress lines of the Kranskop sandy clay derived from granitic gneiss in Figure 2.4h are very widely spaced, illustrating a rapid increase in bulk density for an increment of applied pressure. This is reflected in a high C_{mod} of 0.460 for this soil (21A, Table 2.4). It is interesting to note that these soils at Lothair have long been regarded as "highly compacted" by forestry management despite the high clay contents (>40%).

The compaction response to applied pressure of granite derived soils consistently show steep iso-stress lines in the W-P-D diagrams (Figure 2.4i - k) indicating the dependence of compaction response to applied pressure on water content. This is a reflection of field behaviour of many granite derived forestry soils which have a high bearing capacity when dry (high strength) and become very soft when moist or wet.

The steep iso-stress lines of the Clovelly sandy clay loam derived from sandstone (Figure 2.4l) demonstrates the dependence of compaction behaviour of this soil on water content. This soil is extremely hard below a water content of 0.1 (kg kg^{-1}) and is thus relatively incompressible.

As the soil water content increases, the soil rapidly loses its strength and the compaction behaviour changes sharply for an increase in water content of less than 0.04 kg kg^{-1}. Once again this illustrates the hardsetting nature of some forestry soils (Mullins *et al.*, 1989). Soils such as the Clovelly sandy clay loam (20A) derived from Ecca sandstone in eastern Transvaal are often difficult to manage due to a combination of moderately high compressibility (C_{mod} = 0.397, Table 2.4) and rapid strength changes with small fluctuations in water content.

2.3.2 Predicting the effect of applied pressure and water content on soil compaction

An empirical model, shown in Equation 2.5, was fitted to the data of the 35 forestry soils studied in order to compare the influence of applied pressure and water content on compaction behaviour between soils. This was achieved by considering the relationships presented in Figure 2.4 (a - l) and carrying out stepwise multiple regression (backwards option) following Draper and Smith (1981). This model can be also be used to generate information of the type presented in Figure 2.4 (a - l). The model was similar to the laboratory compaction model of Amir *et al.* (1976) (Equation 2.2), and O'Sullivan (1992) and was found to be the most suitable to evaluate the compaction behaviour of the forestry soils in this study. This model represents bulk density as a function of applied pressure and water content (Equation 2.5).

$$\rho_b = a\,(\theta_m - \theta_{mr}) + C\log(\sigma_r - \sigma) + \rho_{bk} \qquad [2.5]$$

where ρ_b is the bulk density in Mg m^{-3}, a is a constant indicating the relative influence of water content on the compaction process, θ_{mr} is the residual mass water content, θ_m is the mass water content, C is the compression index, that is, the slope of the linear portion of the compression curve. C was calculated using regression equations from all the data points along the linear portions of the compression curves (Larson et al., 1980). C_{mod} will be used from now on to define the compression index of the model to distinguish it from C_{max} (maximum compression index) which is used in Chapter 3. σ is the applied pressure in kPa. For all the models describing compaction behaviour in this work, σ_r was the pressure at which a compression curves became a straight line for the plot of bulk density against the logarithm (base 10) of applied pressure (see Figure 2.4 (a - l)). Similar to the results of Larson *et al.* (1980) and O'Sullivan (1992), σ_r was usually about 100 kPa. In this study the lowest water content θ_{mr} approximated wilting point. The constant ρ_{bk} is the bulk density at σ_r (usually 100 kPa) and the lowest water content θ_{mr}.

The constant a is similar to the term S_T of Larson *et al.* (1980), (Equation 2.4) and Δ_T of Gupta and Larson, (1982) except that these authors expressed it in terms of the slope of bulk density against degree of saturation for a given applied pressure. In this study a is essentially the slope of bulk density against water content (kg kg^{-1}) for a given applied pressure.

Table 2.4 summarises the regression parameters derived from Equation 2.5 for all the forestry soils in this study. A compaction code has been allocated to each soil in Table 2.4, indicating the relative type of compression behaviour associated with each soil. These are briefly outlined below:

L : Low compressibility (C_{mod} < 0.3)
M : Moderate compressibility (C_{mod} 0.3 - 0.4)
H : High compressibility (C_{mod} > 0.4)

L to H followed by;

I : Water content insensitive (a < 1.5)
S : Water content sensitive (a > 1.5)

Inspection of Table 2.4 shows that with the exception of one soil (26A), the multiple correlation coefficient R exceeded 0.89 for all of soils studied. For all soils R was significant at the 1% probability level. Lower values of R (< 0.92) could be attributed to the relatively inconsistent response of bulk density to applied pressure for different water contents for sandy soils from Zululand with less than 12% clay (11A to 15A, Table 2.4). This behaviour is borne out by the a values in Table 2.4 being close to 0 for the sandy soils 12A and 13A, indicating that compaction response was independent of water content. The negative a values of 11A and 15A demonstrate that, on average, the higher the water content the lower the bulk density increase for an increment of applied pressure.

The regression coefficients of each virgin compression line (C_{mod}) for each soil were compared to see if significant differences were apparent between lines. This was achieved by dividing the differences between the regression coefficients (C_{mod1} - C_{mod2}) by the estimate of variation around the regression times the sum of squares (Steele and Torrie, 1981, p258). No significant differences were detected between C_{mod} for any of the soils studied even though C values were much lower for soils undergoing compression near wilting point than when moist or wet. Larson *et al.* (1980) reported that in only 7 out of 36 soil samples were values of C significantly different at different water contents.

Table 2.4 shows that C_{mod} ranges from 0.082 for relatively incompressible sandy soils to 0.516 for highly compressible clay soils. According to Bradford and Gupta (1986) C_{mod} values usually range from between 0.2 and 2.0. The results in this study compare favourably with those elsewhere. Larson *et al.* (1980) presented *C* values of between 0.22 and 0.59 for a range soils from each of the seven orders of Soil Taxonomy. Low *C* values of 0.20 to 0.23 were reported for two eutric cambisols and a gleysol from Scotland (O'Sullivan, 1992). Saini et al. (1984) presented *C* values ranging from 0.153 to 0.245 for loams and silty clay loams respectively.

2.3.3 Relationships between constants and coefficients in the compaction model and selected soil physical properties

Scatter plots of all the relationships between soil physical properties and the regression coefficients in the compaction model (Equation 2.5) were examined and the data subjected to single and multiple regression analysis according to Draper and Smith (1981). As a high degree of covariance existed between variables, rendering them non-independent, multiple regression involving more than one independent variable was not regarded as suitable.

Relationships between C_{mod} and selected soil physical properties are presented in a correlation matrix (Table 2.5) and graphically in Figures 2.5 to 2.8. The regression equations are summarised for clarity in Table 2.6. In combination with Equation 2.5 these may be used to determine a suite of compression curves for a particular soil with a knowledge of any of the soil physical properties presented in Table 2.6. Validation of this model is presented later in this chapter. A more detailed discussion of the interpretation of the relationships between compression index and soil physical and chemical properties is given in Chapter 3.

Highly significant quadratic relationships were obtained between C_{mod} and percent clay plus silt, percent clay and percent organic carbon (LOI) (Table 2.6). Highly significant negative linear relationships were noted between C_{mod} and fine sand and medium sand (Table 2.5). C_{mod} was particularly well predicted by clay plus silt and clay content (Figures 2.5a and 2.6a). Figure 2.5a illustrates that C_{mod} values are highest when clay plus silt contents are between 55 and 75%. Above clay plus silt values of 75% there is considerable scatter in the data points, probably due to widely varying organic matter contents in these soils.

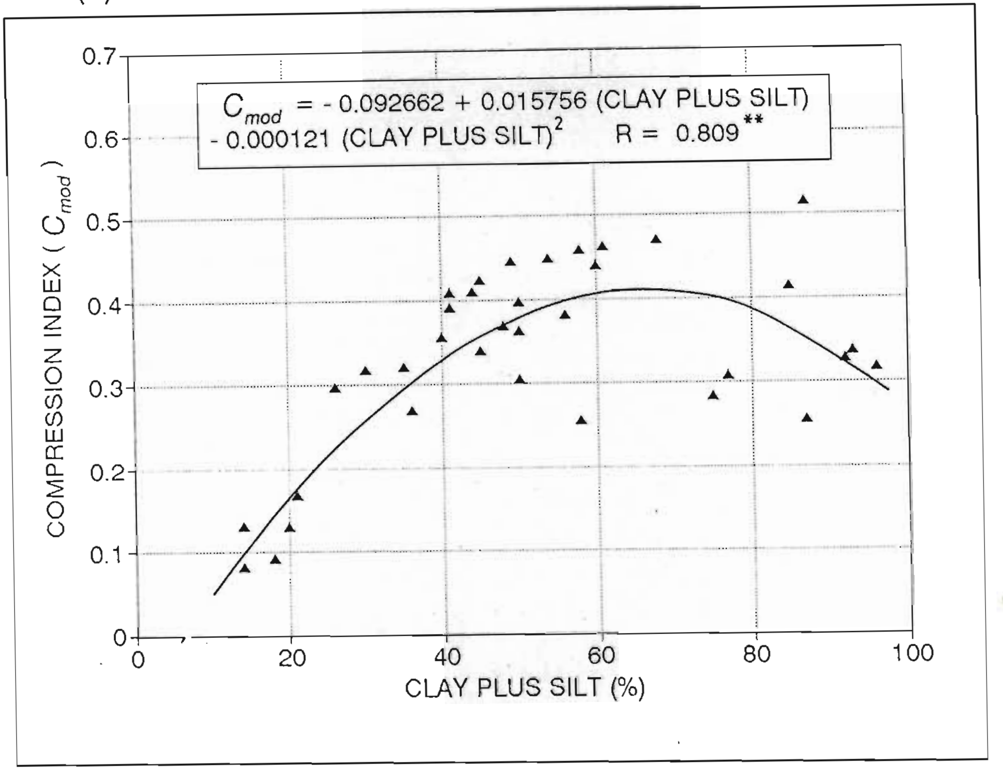
Table 2.5: Partial correlation matrix of relationships between constants in the compaction model (Equation 2.5) and selected soil physical properties.

	C_{mod}	a	ρ_{bk}
C_{mod}	1.000 **		
a	0.622 **	1.000 **	
ρ_{bk}	-0.627 **	-0.199	1.000 **
CLAY + SILT	0.508 *	0.109	-0.893 **
ORG C (LOI)	0.247	-0.205	-0.831 **
ORG C (WB)	0.373	-0.218	-0.652 **
CLAY	0.489 *	0.222	-0.866 **
FINE SILT	0.181	-0.119	-0.392
COARSE SILT	0.415	-0.040	-0.664 **
FINE SAND	-0.612 **	-0.337	0.809 **
MEDIUM SAND	-0.662 **	-0.287	0.888 **
COARSE SAND	0.383	0.522 *	0.014
	C_{mod}	a	ρ_{bk}

* Denotes r values significant at 0.05 probability level

** Denotes r values significant at 0.01 probability level

(a)



(b)

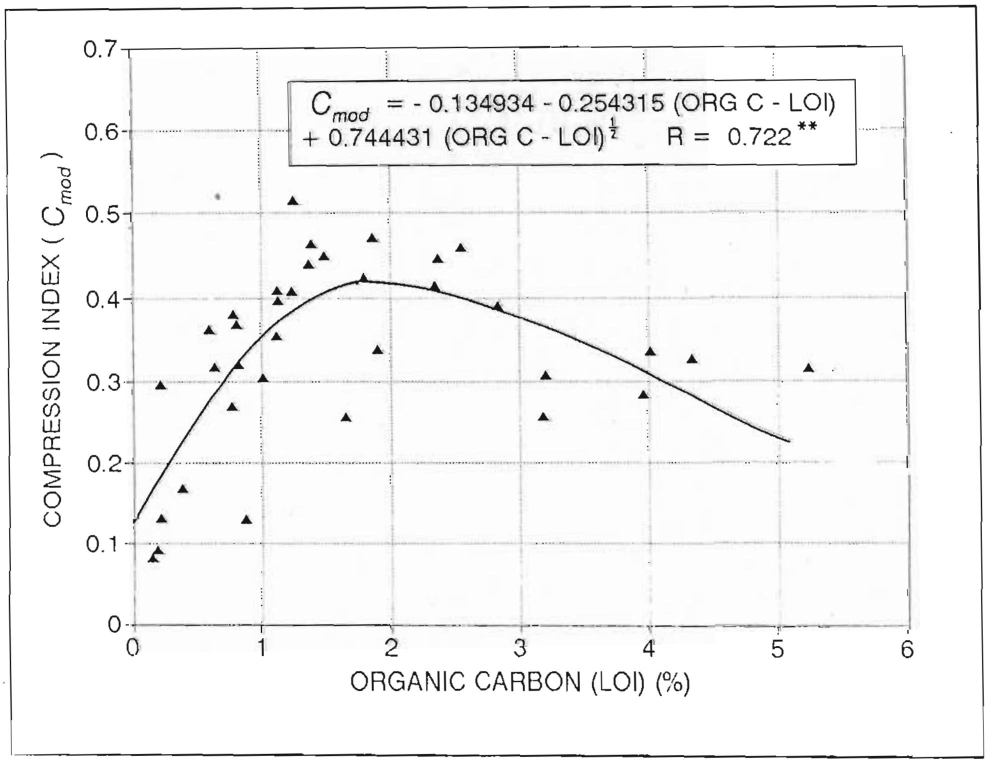
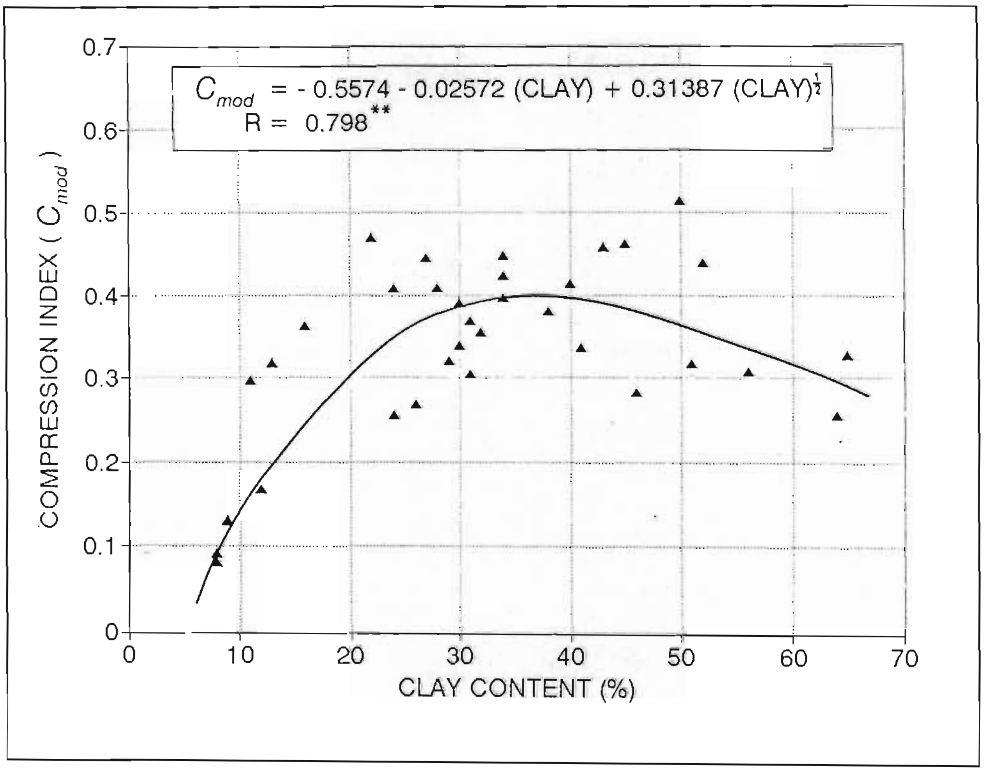


Figure 2.5: Relationships between compression index (C_{mod}) and (a) clay plus silt and (b) organic carbon (LOI).

(a)



(b)

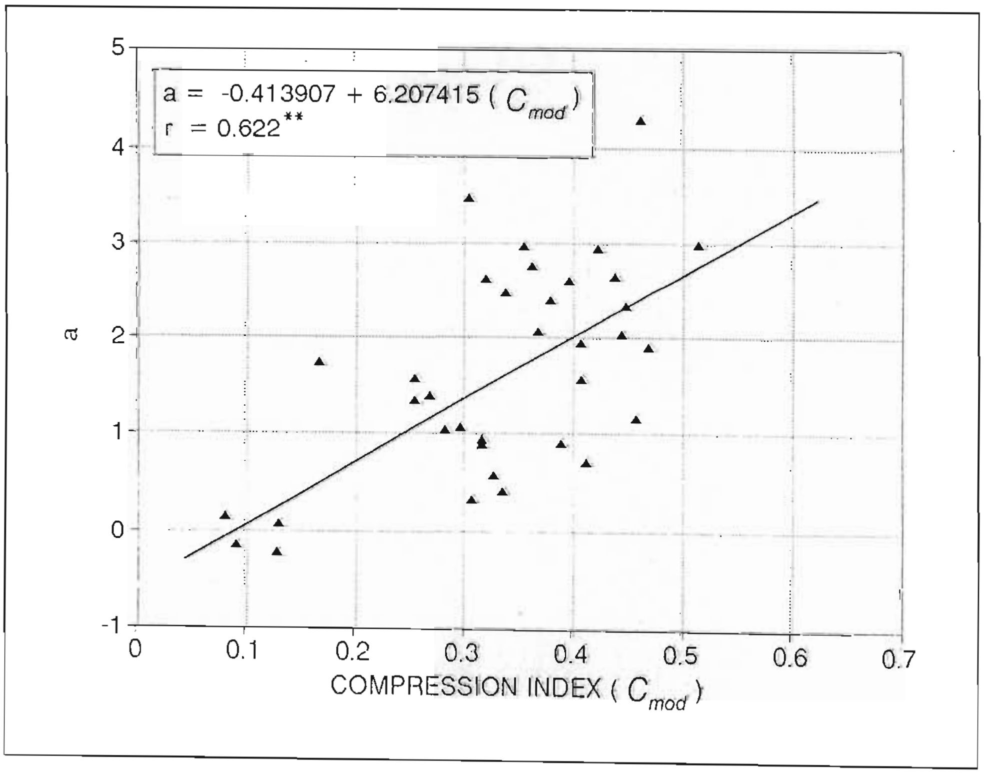


Figure 2.6: Relationships between (a) compression index (C_{mod}) and clay content and (b) between *a* and C_{mod}.

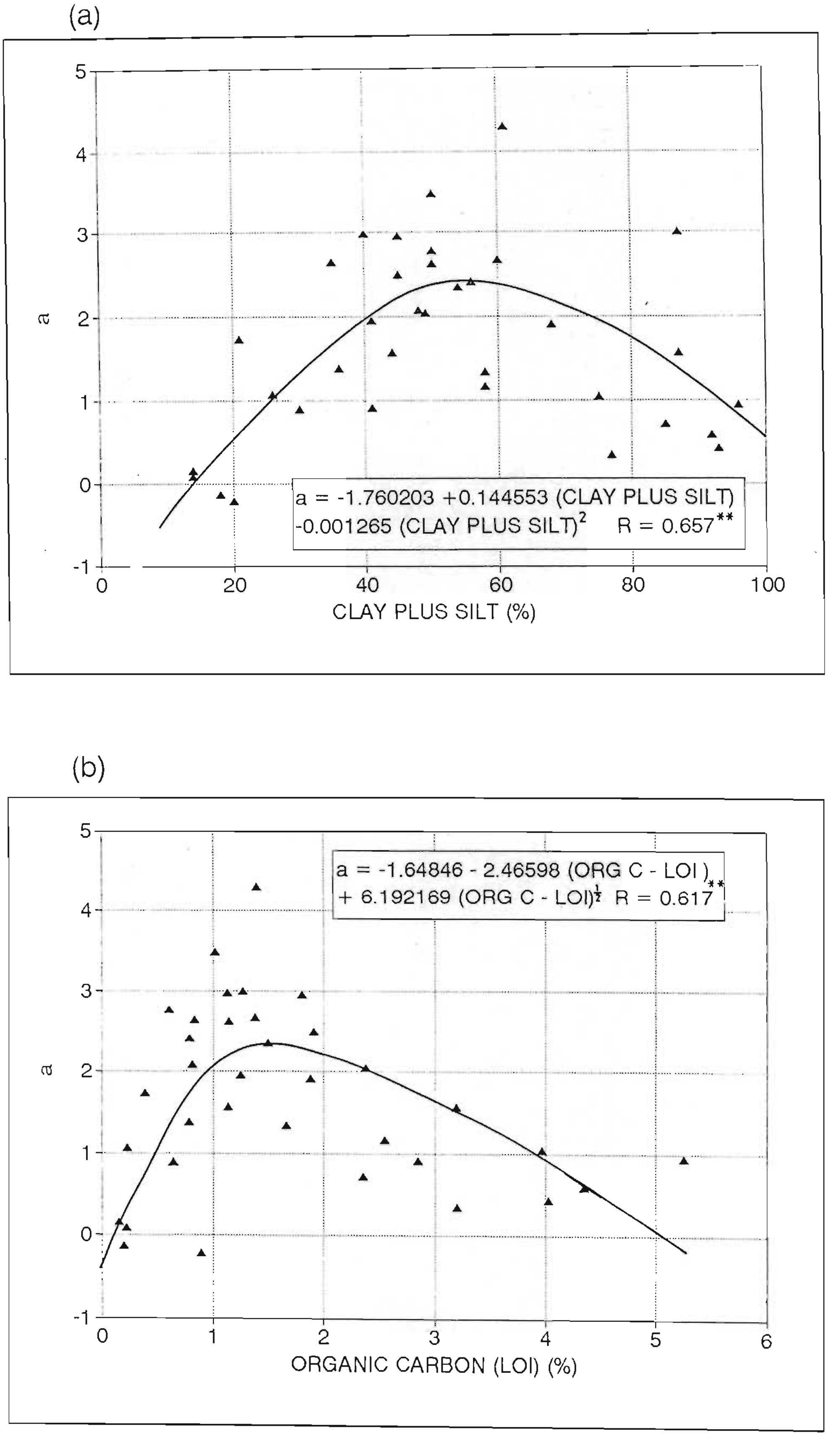


Figure 2.7: Relationships between *a* and (a) clay plus silt and (b) organic carbon (LOI)

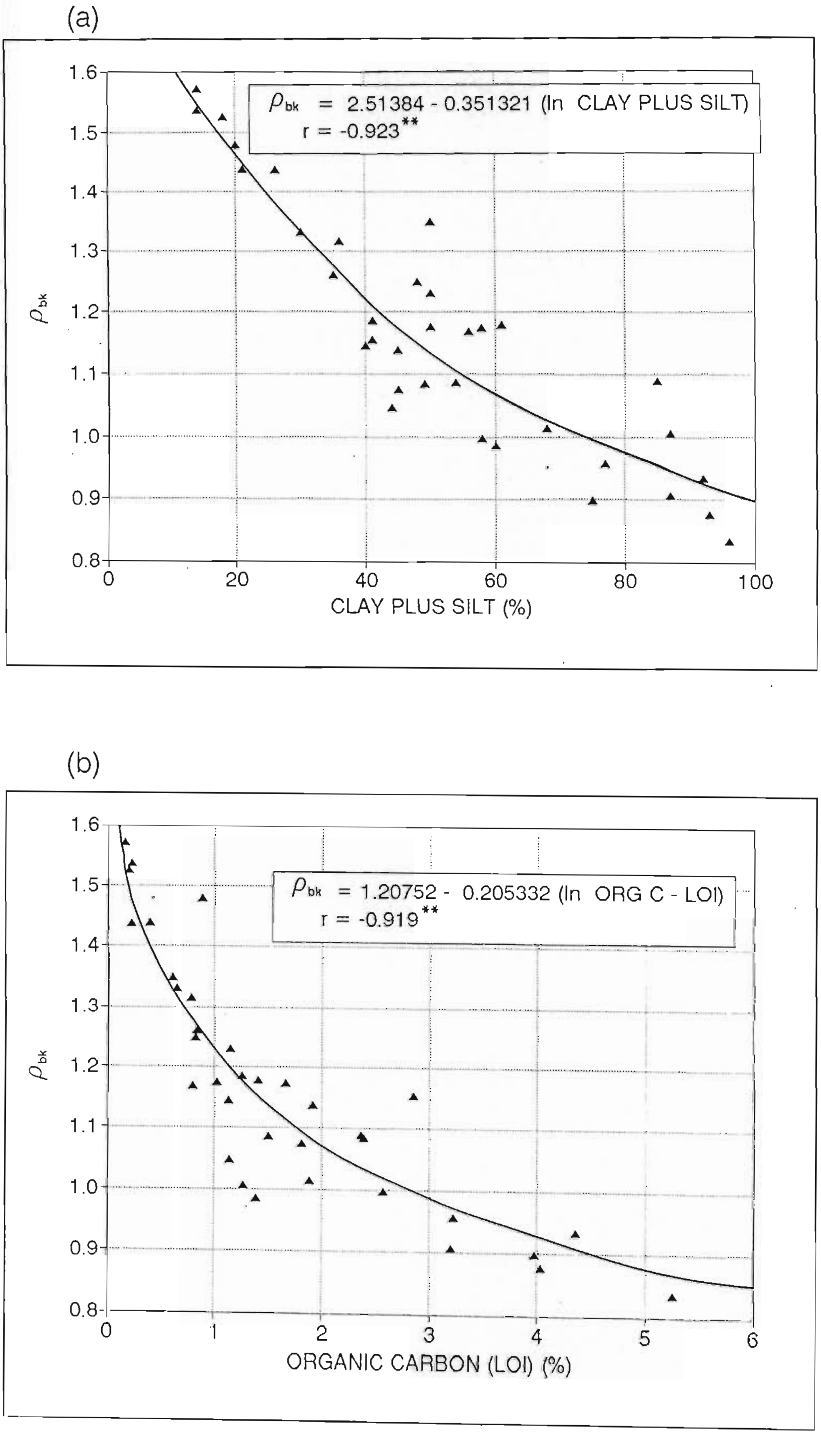


Figure 2.8: Relationships between ρ_{bk} and (a) clay plus silt and (b) organic carbon (LOI)

Table 2.6: Constants and correlation coefficients for the relationships between soil physical properties and the constants and coefficients in the compression model. Thirty five observations were used in each regression. All values of r and R are significant at the 1% probability level.

Variable		Model Type	Regression coefficients and S.E.E.# in brackets			r or R
Dependent (y)	Independent (x)		*k*	*a*	*b*	
C_{mod}	Clay + silt	$k+ax+bx^2$	-0.092262 (0.05452)	0.015756 (0.00215)	-0.000121 (0.00002)	0.809
C_{mod}	Org C (LOI)	$k+ax+bx^{1/2}$	-0.134934 (0.07679)	-0.254315 (0.04794)	0.744431 (0.12661)	0.722
C_{mod}	Clay	$k+ax+bx^{1/2}$	-0.5574 (0.06848)	-0.02572 (0.00497)	0.31387 (0.05289)	0.798
a	C_{mod}	$k+ax$	-0.413907 (0.47871)	6.207415 (1.36180)	- -	0.622
a	Clay + silt	$k+ax+bx^2$	-1.760203 (0.69720)	0.144553 (0.02743)	-0.001265 (0.00024)	0.657
a	Org C (LOI)	$k+ax+bx^{1/2}$	-1.64846 (0.89426)	-2.46598 (0.02743)	6.192169 (1.48188)	0.617
ρ_{bk}	Clay + silt	$k+a(\ln)x$	2.51384 (0.09870)	-0.351321 (0.02550)	- -	-0.923
ρ_{bk}	Org C (LOI)	$k+a(\ln)x$	1.20752 (0.01387)	0.20533 (0.01529)	- -	-0.919

: Standard error of estimate

C_{mod} was well correlated with LOI organic carbon but less well with WB organic carbon. It is likely that organic carbon by loss-on-ignition reflects in part clay content due to the inclusion of hygroscopic or adsorbed water in the mass fraction determined during loss on ignition (Donkin, 1991). The relationship between organic carbon (LOI) and C_{mod} is presented in Figure 2.5b and shows that C_{mod} values are highest when organic carbon (LOI) percentages are between 1.5 and 2.5. Table 2.4 shows that the Kranskop silty clay (6A) and Kranskop clay (7A) soils from Natal had C_{mod} values of 0.318 and 0.309 respectively and the Kranskop clay (19A) from Transvaal had a C_{mod} of 0.328. These C_{mod} values indicate that these soils are moderately compressible and are less than those predicted for comparative Oxisols and Ultisols by the model of Larson *et al.* (1980). It is likely that this model will under-predict C_{mod} of South African soils with high organic carbon levels as the soils in the study of Larson *et al.* (1980) possessed organic carbon levels less than 2.5%. The organic carbon contents (WB) of the Magwa and both Kranskop soils ranged from 2.10 to 5.77%. The usefulness of the models of Gupta and Allmaras (1987), in the prediction of compression index of South African forestry soils is discussed in Chapter 3.

The significant relationship between clay content and C_{mod} (Figure 2.6a) supported the results of Gupta and Allmaras (1987) who presented a similar quadratic equation for this relationship. The result in this study was achieved despite grouping all of the soils (from 5 soil orders) into one regression, whereas Gupta and Allmaras (1987) separated the relationship between C and clay content into two soil groupings: Alfisols, Ultisols and Oxisols in one group ($R = 0.76$), and Entisols, Inceptisols, Mollisols, Vertisols and Spodosols in another ($R = 0.79$) because of differences in clay mineralogy.

The sensitivity of the compaction process to changes in water content is indicated by the coefficient a in Equation 2.5. Increasing values of a demonstrate the increasing importance of water content in the compaction process. Higher a values are related to higher compression indices (C_{mod}) as borne out by the significant correlation between these two variables (Table 2.6). This linear relationship is presented in Figure 2.6b. A possible explanation for the correlation between C_{mod} and a is that soils which are highly compressible such as sandy clay loams have rather acute water - strength relationships. Soil strength changes rapidly with changing water content (see Chapter 4) and thus bearing capacity, and this influences compressibility. Soils with between 50 and 65% silt plus clay (i.e. sandy clay loam) possess maximum a values (Figure 2.7a). The degree of covariance between a and the compression index is reflected in the highly significant relationships between *a* and silt plus clay and LOI organic carbon (Figure 2.7a and b).

Gupta and Larson (1982) reported significant relationships between an index of compaction sensitivity to water content, ΔT, which is analogous to *a* in this study. ΔT was correlated with silt content for fine textured soils and clay content for coarse textured soils. In this study no stratification of the data set was necessary to obtain highly significant correlations between measures of soil texture and *a.*

Although high values of C_{mod} are associated with high *a* values, some soils such as 5A and 20A have moderate compressibility but are very sensitive to water content, that is, have high *a* values (Table 2.4). Values of *a* vary from between -0.217 for soils which are relatively water content insensitive to changes in compaction to 4.3 for soils which are highly sensitive to water content. Based on these figures, compaction behaviour is most sensitive to changes in water content for granitic soils from eastern Transvaal and sandstone derived soils in general. The least sensitive to changes in water content are the sandy soils from Zululand, and the dolerite and diabase derived soils.

The constant ρ_{bk} refers to the bulk density at 100 kPa applied pressure at the lowest water content (θ_{mr}), the latter corresponding approximately to wilting point. From field experience it is apparent that in most cases ρ_{bk} approximates "normal" field bulk density of forestry soils. Figure 2.8a and b show that the constant ρ_{bk} was significantly correlated with clay plus silt and organic carbon (LOI). Gupta and Larson (1982) presented a similar equation relating clay content with initial bulk density at an applied pressure of 100 kPa and 50% saturation.

2.3.4 Model validation

The relationships between the constants in Equation 2.5 and selected soil physical properties enable the prediction of compaction behaviour for a soil with known soil physical characteristics such as silt plus clay percentage and organic carbon content. To test the usefulness of the model three soils were chosen representing a range of textures and organic carbon contents. These are briefly described below:

Soil form	Soil texture	Clay plus silt	Org C (LOI)
Clovelly	Silty clay	87	1.72
Inanda	Loam	69	2.00
Avalon	Sandy loam	38	0.48

The predicted values of C_{mod}, a and ρ_{bk} were determined from the best regression model for that constant. In other words, clay plus silt percentage was used to determine C_{mod} and *a*, and organic carbon (LOI) for ρ_{bk} (see Table 2.6). The results are presented in Figure 2.9(a - c) for the Clovelly silty clay, Inanda loam and Avalon sandy loam respectively. Each figure shows generally good agreement between measurement and prediction. It is important to note that the model is valid only for applied pressures between 100 and 1400 kPa and as such the model essentially approximates the virgin compression line. Often dry soils, particularly soils which are resistant to compaction, display a non linear compression curve (when applied pressure is plotted on a log scale) for applied pressures between 100 and 400 kPa. In such cases the model will slightly under-predict bulk density, though practically this is not a major problem as the change in compaction is small for dry soils. As a soil approaches saturation the curve will become non-linear and the model will not apply. According to Larson *et al.* (1980), this occurs at matric potentials greater than -5.0 kPa. This behaviour is evident in Figure 2.9a for the Clovelly silty clay at a water content of 0.283 kg kg^{-1}. The compression curve becomes non-linear as the soil becomes saturated at this water content and at a bulk density of approximately 1.6 Mg m^{-3}.

2.3.5 Practical interpretation of compaction behaviour

Harvesting operations continue all year round in South African forestry plantations. Extension scientists are faced with the task of advising harvesting foresters and planners about the relative risk of soil compaction occurring under diverse soil conditions and water regimes. The information presented in this chapter can be used as an immediate guide to the relative importance of applied pressure and water content on the compaction process for a wide range of forestry soils.

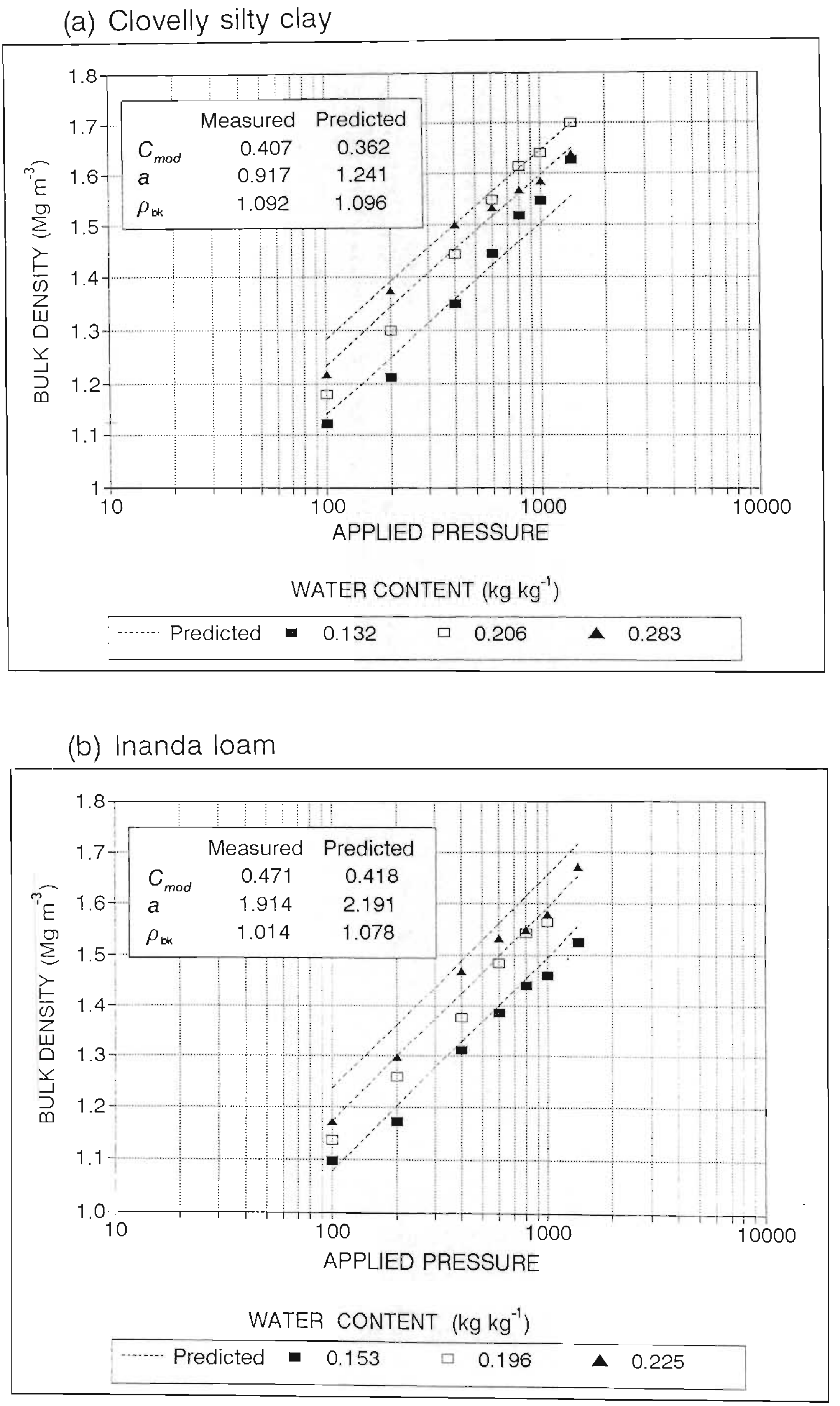


Figure 2.9: Model validation lines showing predicted and measured virgin compression lines for (a) a Clovelly silty clay, (b) an Inanda loam and

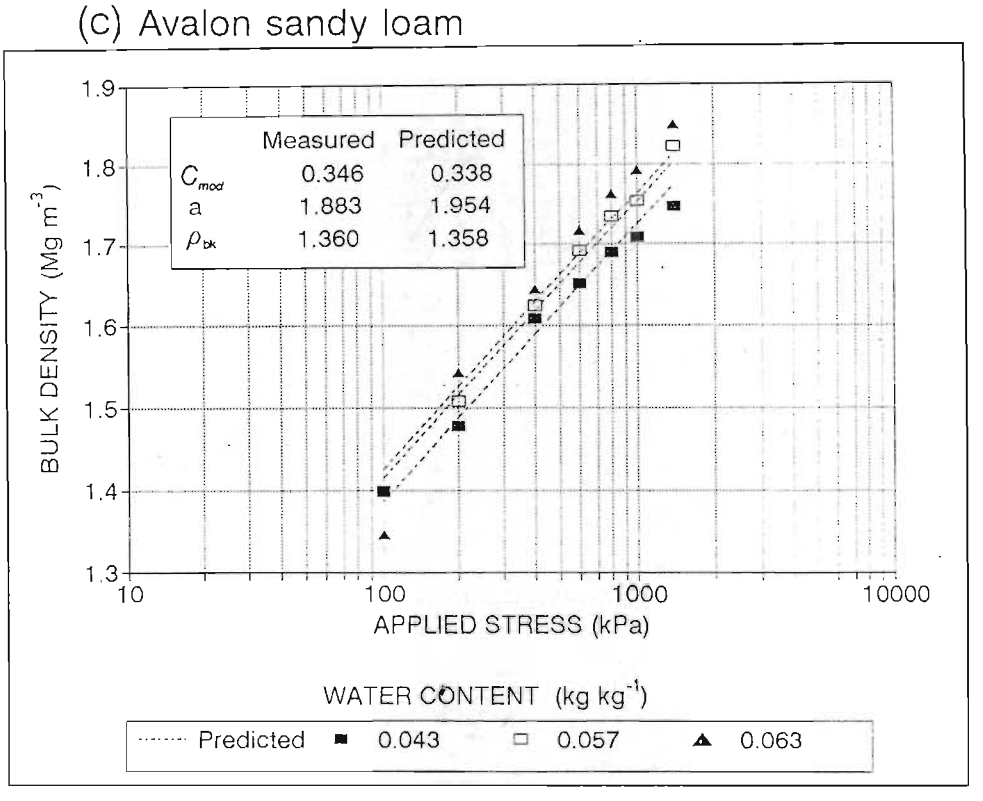


Figure 2.9 (continued): Model validation lines showing predicted versus actual virgin compression lines for (c) an Avalon sandy loam.

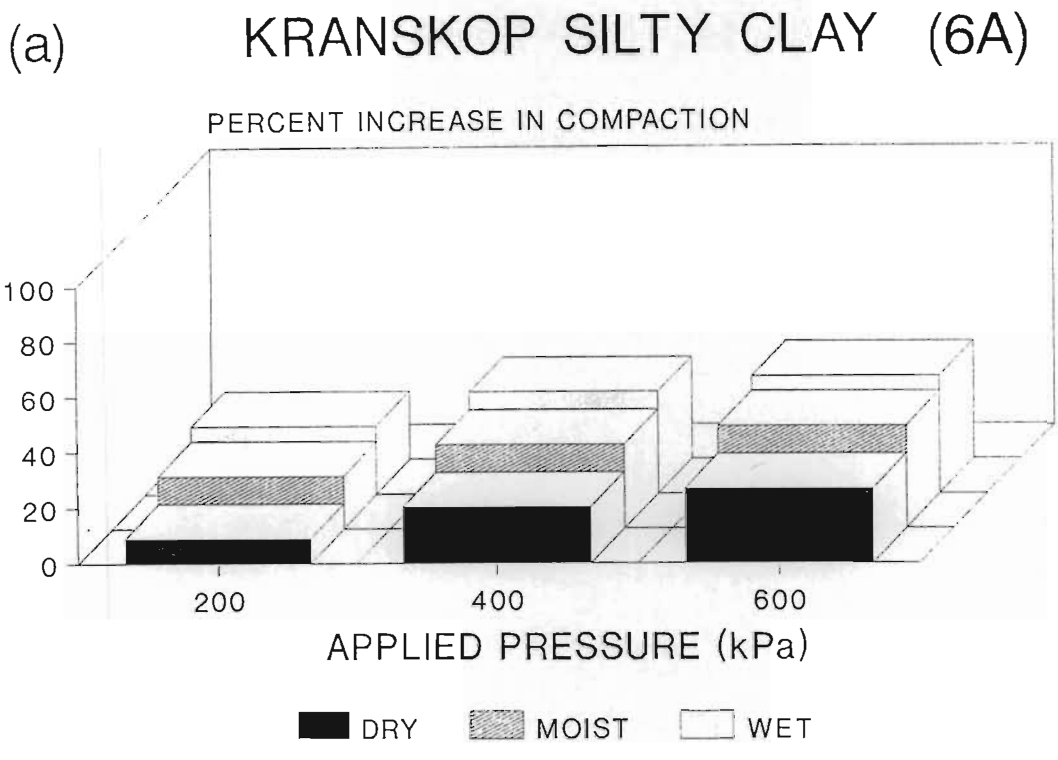
Figure 2.10 (a - d) shows the percentage increase in compaction (increase in bulk density over initial bulk density) as a result of varying applied pressures and water contents for four different forestry soils. These results have been calculated for each soil from constants derived from the model (Equation 2.5) and reported in Table 2.4.

The percentage increase in compaction following varying increases in applied pressures at three water contents for the Kranskop silty clay (6A) is shown in Figure 2.10a. It is immediately clear that although the C_{mod} for this soil is relatively low (0.318) the main factor influencing compaction is applied pressure rather than water content at the time of compaction. The minor role of water content in affecting compaction is indicated by the very low *a* value of 0.835 (6A, Table 2.4). Therefore, doubling of the ground pressure from 200 to 400 kPa substantially increases the level of compaction even when the soil is dry and has a similar effect to compacting the soil with 200 kPa of ground pressure when the soil is wet. Thus for forestry management there are no benefits of waiting for the soil to dry out before commencing extraction operations. The greatest overall advantage in reducing compaction on this soil would be to reduce overall axle load and minimise passes regardless of water content. This result confirms the results and observations of Smith (1992b) in a compaction forestry field trial on the same soil form. Despite dry to moist conditions existing at the time of the compaction treatments, substantial increases in compaction occurred with increasing number of passes of a T14 forwarder (loaded weight 14 tonnes). One pass of the forwarder had little effect on increasing compaction, but after 5 passes of the machine significant increases in compaction were recorded to a depth of 70 cm.

Figure 2.10b shows that increases in compaction are almost independent of water content (a = 0.888) for a Cartref sandy loam. Increases in soil compaction are almost entirely due to increasing ground pressure though these are not high either due to the moderately low C_{mod} (0.318) of the Cartref sandy loam (Table 2.4). As these soils are water content insensitive there is unlikely to be any benefit in preferentially scheduling harvesting operations on these soils to a particular season.

Soils with high a values such as the Hutton sandy clay loam (a = 2.972) are extremely sensitive to water content at the time of compaction. Figure 2.10c shows that the percent increase in soil compaction for the Hutton sandy clay loam is related more to changes in water content than to applied pressure. A ground pressure of only 200 kPa when the soil is wet results in a similar increase in compaction (60%) to a ground pressure of 600 kPa when the soil is moist. Scheduling harvesting operations on these soils to drier periods will have the greatest benefit in lowering soil compaction, notwithstanding changes in ground pressure.

Soils possessing both high C_{mod} and a values, such as the Kranskop clay (C_{mod} = 0.463; a = 4.302), should be trafficked in dry periods and with as low a ground pressure as possible. Applying moderate ground pressures of 400 kPa when the soil is moist results in an increase in compaction of more than 60% (Figure 2.10d). This increases to nearly 80% when the soil is wet. It is no coincidence that many granite and gneiss derived soils, particularly sandy clays, sandy clay loams and clays, are known to possess severe compaction problems despite their relatively high clay contents.



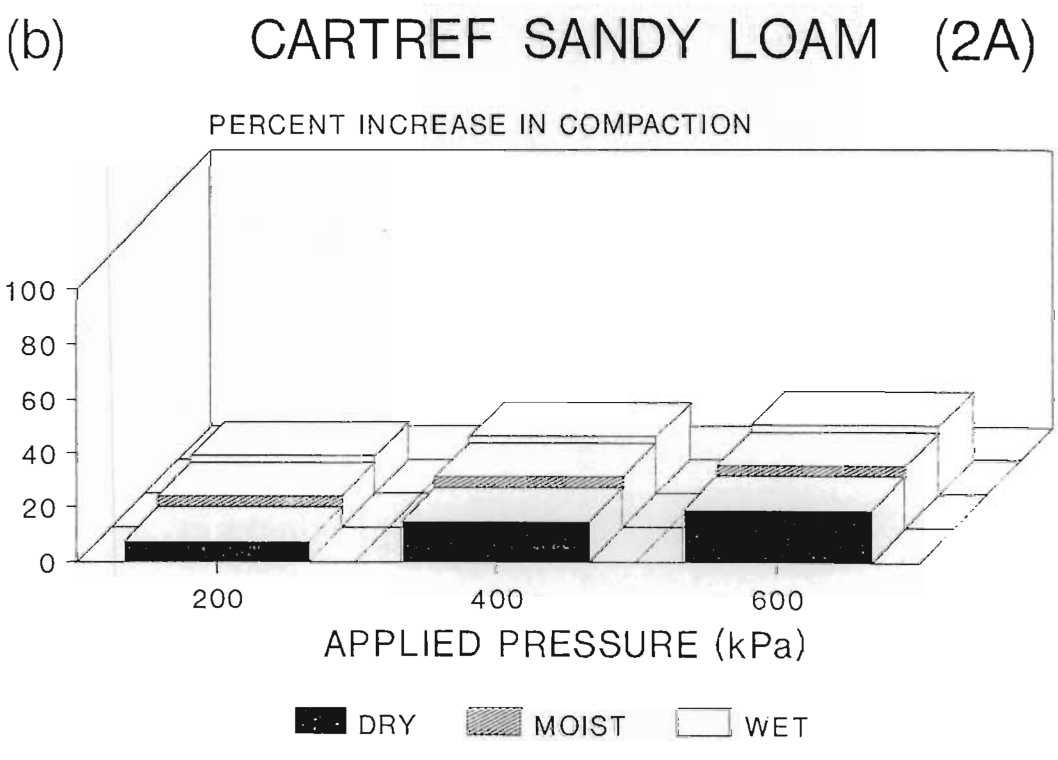
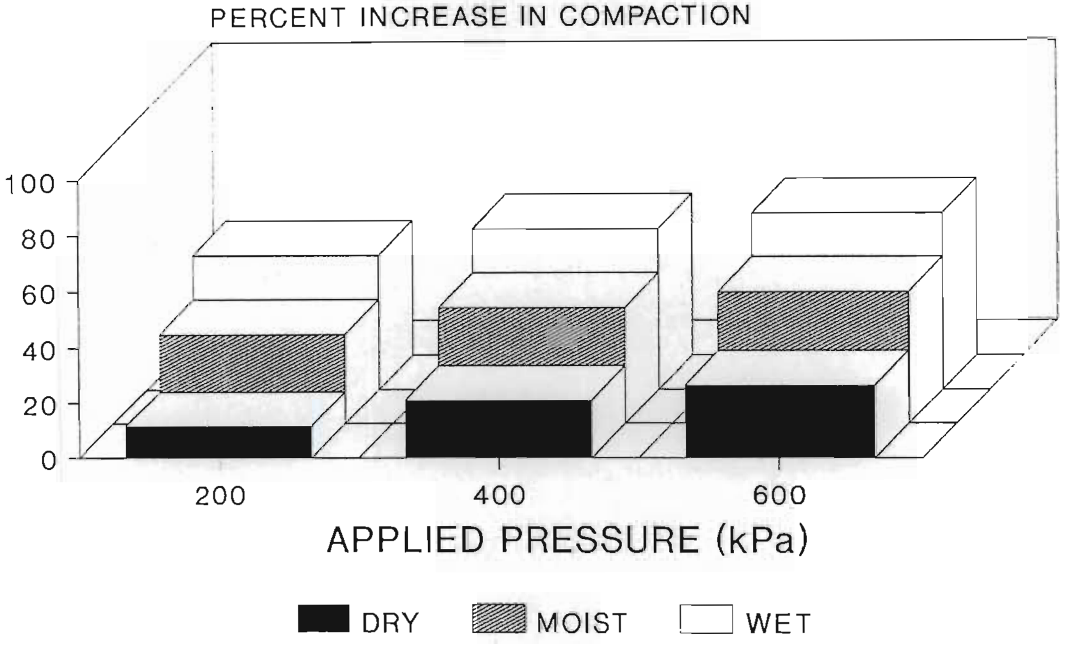


Figure 2.10: The effect of applied pressure and water content on soil compaction for selected forestry soils.

(c) HUTTON SANDY CLAY LOAM (22A)



(d) KRANSKOP CLAY (21B)

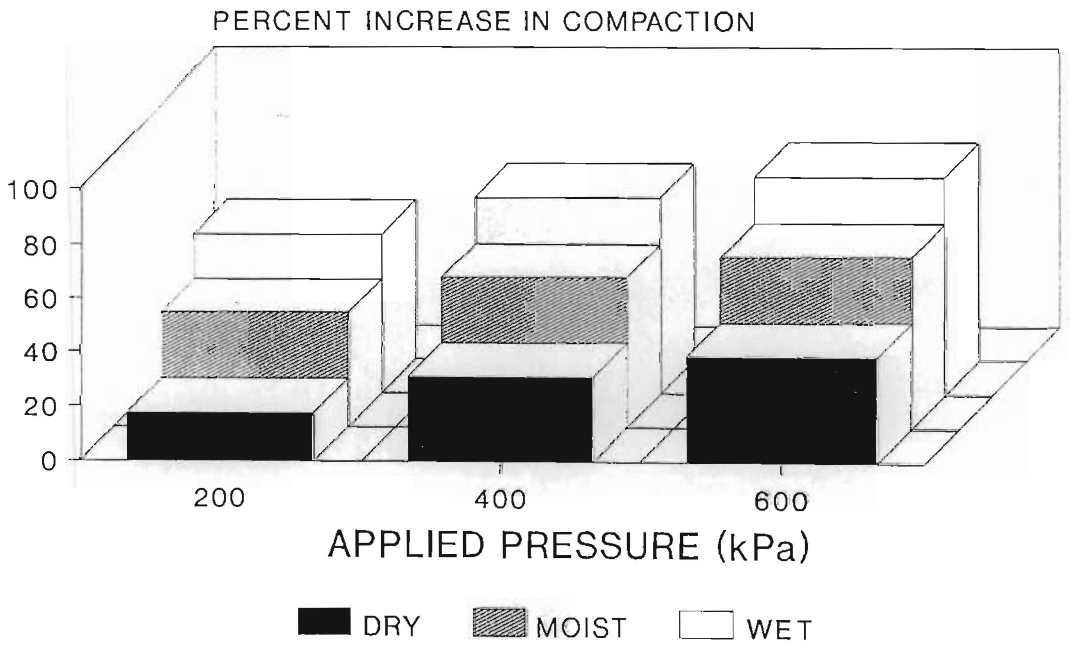


Figure 2.10 (continued)

2.4 CONCLUSIONS

W-P-D diagrams and semi-log plots of bulk density against applied pressure (compression curves) successfully described the compaction behaviour of a number of forestry soils and provided a means with which to compare the effects of applied pressure and water content on changes in soil compaction. The range of water contents and applied pressures commonly encountered in harvesting and tillage operations in timber plantations and how they effect bulk density can be described by Equation 2.5. This model accounted for a considerable proportion of the variation in bulk density for all the data sets of a wide range of forestry soils.

Regression equations were developed which enabled the estimation of constants and coefficients in Equation 2.5 by using soil properties that are recorded and measured on a regular basis, such as clay plus silt percentage or organic carbon content (LOI). For an increment of applied pressure at any given water content, soils with between 55 and 75% clay plus silt and between 1.5 and 2.5% organic carbon (LOI) underwent the greatest increase in compaction as measured by the compression index (C_{mod}). Similarly, the role of water content in the compaction process was most important for soils having between 45 and 65% clay plus silt, and least important for soils with high organic carbon levels (> 3%) and sandy soils with less than 20% clay plus silt.

This study has distinguished itself from others by including soils with a wide range of organic carbon contents as well as particle sizes for soils which are predominantly kaolinitic in nature. Inasmuch as local geology affects particle size distribution and organic carbon content, it has been shown to be an effective way of establishing a first approximation of the likely compression behaviour of forestry soils.

A compaction code which is a qualitative measure of compaction behaviour based on values of constants and coefficients in the compression model (Equation 2.5) showed, for example, that soils developed from granite and sandstone (sandy clay loams and finer) are moderately to highly compressible and that the compaction process is highly dependent on water content. Water content at the time of compaction affects the compaction behaviour to a lesser extent for soils developed from base-rich parent materials such as dolerite and diabase, these soils possessing low to moderate compressibility. This study has shown that a large group of soils which possess predominantly 1:1 clay minerals and are rich in iron oxides can have very different compaction behaviour. This would suggest that grouping these soils together as reported by Larson *et al.* (1980) may not be accurate.

The importance of soil texture in determining the relative importance of water content and applied pressure in the compaction process has been highlighted. Furthermore it has been shown that the same soil forms can have widely different compaction behaviour when interpreted from a practical point of view. The work presented in this chapter indicates that as the present classification system in South Africa (Soil Classification Working Group, 1991) places very little emphasis on particle size distribution, the classification has limitations in providing soil information of value to forestry land users. This aspect will be addressed in more detail in Chapter 3.

CHAPTER 3

SOIL PROPERTIES AFFECTING THE COMPACTIBILITY AND COMPRESSIBILITY OF SOUTH AFRICAN FORESTRY SOILS

3.1 INTRODUCTION

Soil compaction has long been recognised as a major factor affecting plant and crop growth (Bennie and Krynauw, 1985; Hakansson *et al.*, 1988; Raghavan *et al.*, 1989). Although the effects of soil compaction on tree growth varies in magnitude for different tree species (Froehlich, 1979; Graecen and Sands, 1980; Lockaby and Vidrine, 1984), compaction in a forestry setting has a major influence on future soil management strategies (Mckee *et al.*, 1985; Firth and Murphy, 1989). An appraisal of soil compactibility and compressibility is necessary to establish the likely effects of forestry operations on soil compaction. From a conceptual point of view soil compactibility and compressibility are influenced by **external** factors, such as applied pressure which was dealt with in Chapter 2, and **internal** factors such as particle size distribution and organic matter content. The focus of this chapter will be on the latter.

Traditional approaches of assessing the compaction susceptibility of soils have usually involved determination of maximum bulk density (MBD) or compression index (*C*). MBD is a useful physical value as it may be used as a reference point to describe the degree of compactness of a soil and the potential for soils to develop high bulk densities. Another useful property determined in parallel with MBD is the critical water content (CWC) which is the water content at which the maximum density is achieved for a given amount of energy (Proctor, 1934). *C* was discussed in Chapter 2 and refers to the ease with which a soil increases in density when subjected to an applied pressure (Gupta and Allmaras, 1987).

The variation in MBD has been widely attributed to changes in particle size distribution. Models relating MBD to clay plus silt were developed by Bennie and Burger (1988). Van Der Watt (1969) concluded that approximately two-thirds of the variation in MBD could be attributed to varying amounts of very coarse sand (1 to 2 mm) and clay plus silt (< 0.02 mm) but presented regression equations suggesting that, in the absence of data on very coarse sand, MBD could be equally well predicted by coarse sand (0.5 to 2.0 mm) and clay plus silt as independent variables. Moolman and Weber (1978) reported that increasing evenness of particle size distribution resulted in higher MBD values. Similarly, grading of the soils as expressed by the coefficient of kurtosis was reported to be one of the most important factors influencing the compactibility of some southern and western Cape irrigated soils (Moolman, 1981) and western Cape viticultural soils (Van Huyssteen, 1989).

Fine sand is often mentioned as an important factor influencing compaction of soils (Bennie and Krynauw, 1985) but the literature is conflicting. Milford *et al.* (1961), Bodmin and Constantin (1965) and Bennie, (1972) reported that sandy loams and loamy sands with high fine sand fractions were highly susceptible to compaction whereas Moolman and Weber, (1978) and Van Huyssteen (1989) concluded that sorting of particle sizes was more important than that of fine sand alone.

It is likely that organic matter plays an important role in the compaction process and it has been reported that decreasing compactibility is related to increasing organic matter content (Saini, 1966; Adams, 1973; Howard *et al.*, 1981). De Kimpe *et al.* (1982) reported that the most important physical properties influencing compaction behaviour were the water retention properties at high matric potential and these were primarily influenced by both clay and organic matter content. However, Van Huyssteen (1989) could not establish an effect of organic matter on MBD but this was probably due to the low organic carbon levels of the soils used in that study.

Compressibility has also been used as a measure of soil compaction susceptibility. Saini *et al.* (1984) calculated *C* for a number of New Brunswick agricultural soils in Canada whereas O'Sullivan (1992) characterised soil response to various tillage treatments by measuring the resultant *C* for each treatment. Regression equations relating *C* to clay content for a range of temperate and tropical soils were presented by Larson *et al.* (1980) and Gupta and Allmaras (1987). *C* generally increased with increasing clay content for both soil groups up to about 35% clay before levelling off and thereafter decreasing with increasing clay content.

The main objective of this chapter is to assess which soil factors are important for the prediction of the compaction susceptibility of a wide range of typical South African forestry soils.

3.2 METHODS AND MATERIALS

3.2.1 Soils

The same 35 soil samples described in Chapter 2 were used in this study. The soils represented a wide range of South African forestry soils with respect to soil texture, organic carbon contents and parent materials.

3.2.2 Physical and chemical analysis

Maximum bulk density (MBD) was determined for a range of forestry soils according to the standard ASTM method (American Society for Testing and Materials, 1985) commonly known as the Proctor test. Approximately 1 kg of 2 mm sieved soil was split into 3 separate portions. After compaction of the first portion successive portions were added to the cylinder and compacted in the same way, each portion being compacted by 25 blows of a 2.5 kg ram from a height of 40 cm. This procedure was carried out over a range of water contents and a plot of water content versus bulk density was obtained and the MBD was recorded (Appendix 3). The water content at which MBD was achieved was termed the *critical water content (CWC)*. This term is preferred over the more widely used optimum moisture content (OMC) which has engineering connotations (Saini *et al.*, 1984).

Compressibility was determined by a modified method of Koolen (1974) and Larson *et al.* (1980), full details of which were recorded in Chapter 2. Two compression indices were calculated, C_{mod} and C_{max}, for each soil. As the compression lines were not always parallel for a range of water contents, the average compression index, C_{mod}, was computed for each soil in Chapter 2. As C values varied with water content at time of compression for most soils, C_{max} corresponded to the steepest virgin compression line for that soil. In the same way that CWC is the water content at which the soil compacts to its maximum bulk density for a given amount of energy in the Proctor test, C_{max} is the maximum potential compression index for a particular soil at a similar critical water content CWC_{cmax}.

The method used for determining percentage water dispersable clay was a modification of the method of Rengasamy *et al.* (1984) and Miller and Baharuddin (1986). Soils were passed through a 2 mm sieve and air dried. 20 g samples of soil were then placed into 300 ml glass centrifuge cylinders to which 100 ml of distilled water was added to give a soil:water ratio of 1:5. The soil solutions were then subjected to end-over-end shaking by mechanical shaking for two hours. The amount of dispersible clay was determined by pipetting 25 ml aliquots of suspension after an appropriate settling time and calculating the amount of clay in suspension after drying in the oven at 110°C overnight.

Particle size distribution was expressed geometrically by the *geometric mean diameter* (GMD) and *geometric standard deviation* (GSDEV) on the premise that natural soil samples display a wide range of particle sizes, making the geometric scale more useful than the arithmetic scale (Shirazi and Boersma, 1984). The use of GMD is particularly valuable in unifying textural classification of diverse systems (e.g. old and new particle size limits in South African soil classification). In addition, the uniformity or diversity of particle size, i.e. degree of sorting, which one would expect to be related to soil compaction properties, is expressed by the GSDEV of a soil sample. Mathematical expressions for calculating GMD and GSDEV are given below:

$$\text{GMD} = \exp a$$
$$\text{GSDEV} = \exp b$$

where:

$$a = 0.01 \sum f_i \ln M_i \qquad [3.1]$$

and

$$b^2 = 0.01 \sum f_i \ln M_i - a^2 \qquad [3.2]$$

The multiplier 0.01 is inserted to convert percent frequencies into fractions, n is the number of particle size fractions, f_i is the percent of total soil mass having diameters equal to M_i where M_i is the arithmetic mean of two consecutive particle size limits.

Other statistical descriptions of frequency distribution of particle sizes are *kurtosis* which refers to its peakedness and *skewness* which refer to its symmetry (Webster, 1979). Standardised skewness and kurtosis were determined for the particle size distribution of each soil.

In order to establish relationships between dependent and independent variables, scatter-plots of all the relationships were generated and examined. Data were subjected to simple correlation and multiple regression analysis, as suggested by Draper and Smith (1981). In some cases the regression was improved by transformation of the base data sets and by including additional variables such as the square and/or logarithm of the independent variable. Step-wise regression was not considered appropriate as strong correlations were obtained either by linear or multiple regression and because of the high degree of covariation between variables rendering them non-independent.

3.3 RESULTS AND DISCUSSION

Compression indices (C_{max}), maximum bulk density (MBD) and their respective critical water contents are presented in Table 3.1. Kurtosis and skewness were calculated from particle size data using a frequency distribution diagram (P. Clarke, 1994, personal communication) and these are presented in Table 3.1. GMD and GSDEV were calculated using the method of Shirazi and Boersma (1984) and are also given in Table 3.1. A partial correlation matrix is presented for the relationships between the main dependent variables (MBD, CWC, C_{max} and CWC_{cmax}) and selected soil physical and chemical properties in Table 3.2. The full correlation matrix between the selected soil physical properties is presented in Appendix 4.

3.3.1 Compactibility and particle size distribution

Inspection of MBD values in Table 3.1 reveals a wide range from 1.21 to 2.00 Mg m^{-3} with corresponding CWC values varying from 0.085 to 0.405 kg kg^{-1}. Although a strict comparison was not carried out, previous field measurements on uncompacted soil (Smith, 1992b; Musto, 1994) have shown that MBD values in this study are approximately 35% higher than field bulk densities for clayey humic soils, 30% higher for loams and about 15% for loamy sands. This can be compared with the study of Van Huyssteen (1989) who found an average increase of only 14% in MBD over field bulk density for 71 vineyard soils from the south western Cape. The higher organic carbon levels in forestry soils and the absence of intensive soil management may have resulted in the smaller difference between field bulk density and MBD found by Van Huyssteen (1989). Figure 3.1 shows the relationship between MBD and water content for selected forestry topsoils. Only the peak of the curve produced by the impact test is shown for each soil (for full curves see Appendix 3). For clarity the soils have been organised into three groupings based on parent materials. MBD values ranged from as low as 1.2 Mg m^{-3} for clayey soils with high organic carbon contents (>3%) to 1.88 Mg m^{-3} for sandy loams with low organic carbon contents (<1%).

Table 3.1: Indices of compactibility and compressibility and selected physical properties for selected South African forestry soils.

Site No. and horizon	Soil form	Soil texture	Cl + Si (%)	Organic Carbon(%) LOI	WB	MBD (Mg m^{-3})	CWC (kg kg^{-1})	C_{max}	CWC_{cmax}	GMD (mm)	GSDEV	Kurtosis	Skewness	Disp. clay (%)*
1A	Lu	Lm	68	1.88	4.02	1.55	0.230	0.523	0.19	0.025	10.082	-1.201	1.523	20.73
2A	Cf	SaLm	30	0.65	1.42	1.82	0.140	0.330	0.16	0.089	9.184	-0.961	-3.243	11.38
2E	Cf	SaLm	26	0.23	0.32	2.00	0.100	0.311	0.07	0.114	6.815	-0.857	-3.118	21.47
3A	Lu	Lm	58	1.66	2.37	1.68	0.180	0.444	0.16	0.031	11.954	-2.047	0.837	10.28
4A	Ma	SiCl	93	4.03	2.10	1.21	0.405	0.389	0.32	0.008	6.812	2.968	4.433	5.48
5A	Ia	SaClLm	45	1.91	2.15	1.84	0.155	0.456	0.15	0.040	16.163	-2.981	-0.604	9.12
6A	Kp	SiCl	96	5.25	5.77	1.31	0.370	0.389	0.36	0.005	4.146	3.854	5.193	8.76
6B	Kp	Cl	75	3.97	2.64	1.30	0.380	0.412	0.30	0.012	13.410	-1.015	3.573	9.85
6B2	Kp	Cl	87	3.20	1.09	1.40	0.355	0.382	0.35	0.005	11.901	3.991	6.960	1.06
7A	Kp	Cl	77	3.21	4.22	1.39	0.350	0.411	0.23	0.009	21.713	-0.097	4.446	8.64
8A	Ia	SiClLm	85	2.36	3.58	1.52	0.255	0.531	0.20	0.010	6.873	0.731	4.103	11.78
8B	Ia	Cl	87	1.27	1.06	1.72	0.210	0.598	0.14	0.008	10.538	1.778	5.453	19.88
9A	No	SaClLm	49	2.38	3.83	1.70	0.205	0.520	0.09	0.041	13.581	-2.792	-0.069	8.04
10A	Cf	Lm	50	0.61	0.95	1.93	0.130	0.397	0.14	0.040	7.539	-1.945	-0.576	17.41
11A	Fw	LmSa	18	0.20	0.29	1.73	0.128	0.132	0.14	0.112	4.390	1.631	-5.253	10.90
12A	Fw	LmSa	14	0.16	0.26	1.78	0.153	0.100	0.13	0.135	4.319	3.409	-5.884	11.82
13A	Fw	LmSa	14	0.23	0.38	1.84	0.085	0.114	0.14	0.139	5.814	3.091	-5.601	14.45
14A	Hu	SaLm	21	0.39	0.43	1.89	0.125	0.248	0.12	0.111	6.279	0.264	-4.060	7.21
15A	Fw	LmSa	20	0.89	1.65	1.66	0.180	0.145	0.11	0.127	7.365	1.373	-4.418	30.32
16A	No	SaClLm	41	1.25	2.36	1.75	0.155	0.481	0.13	0.060	13.684	-2.732	-1.132	12.96
17A	Hu	SaClLm	36	0.78	1.49	1.72	0.135	0.368	0.08	0.060	10.952	-2.725	-2.019	10.15
17B	Hu	SaClLm	35	0.84	1.09	1.96	0.130	0.387	0.09	0.065	17.133	-2.960	-1.826	17.36
18A	Ia	SaClLm	44	1.14	2.42	1.65	0.180	0.431	0.13	0.037	12.254	-2.702	-0.553	19.49
19A	Kp	Cl	92	4.36	4.13	1.27	0.365	0.438	0.24	0.004	12.559	3.675	6.053	0.03
20A	Cv	SaClLm	50	1.14	1.37	1.88	0.130	0.498	0.12	0.034	18.683	-3.098	0.312	4.56
20B	Cv	SaClLm	50	1.02	0.92	1.85	0.150	0.508	0.13	0.039	15.893	-3.113	0.056	0.21
21A	Kp	SaCl	58	2.56	4.23	1.52	0.225	0.577	0.20	0.025	23.394	-3.218	1.376	17.18
21B	Kp	Cl	61	1.40	1.05	1.82	0.150	0.523	0.15	0.024	25.642	-3.235	1.671	0.00
22A	Hu	SaClLm	40	1.13	1.21	1.90	0.130	0.503	0.13	0.053	18.335	-3.218	-1.199	44.96
22B	Hu	Cl	60	1.38	0.34	1.69	0.205	0.599	0.20	0.016	20.286	-3.123	1.897	0.00
23A	Sw	SaClLm	54	1.50	1.57	1.73	0.160	0.545	0.16	0.027	13.900	-2.964	0.424	21.85
24A	Sw	SaClLm	48	0.82	1.94	1.82	0.160	0.533	0.13	0.044	15.408	-3.324	-0.491	32.70
24B	Sw	ClLm	56	0.80	1.46	1.66	0.165	0.555	0.14	0.029	18.833	-3.279	0.840	30.08
25A	Ia	SaClLm	45	1.81	2.85	1.74	0.210	0.472	0.16	0.055	22.401	-3.574	-0.836	33.80
26A	Ma	SaClLm	41	2.85	3.42	1.59	0.230	0.437	0.19	0.062	17.168	-3.284	-1.478	14.91

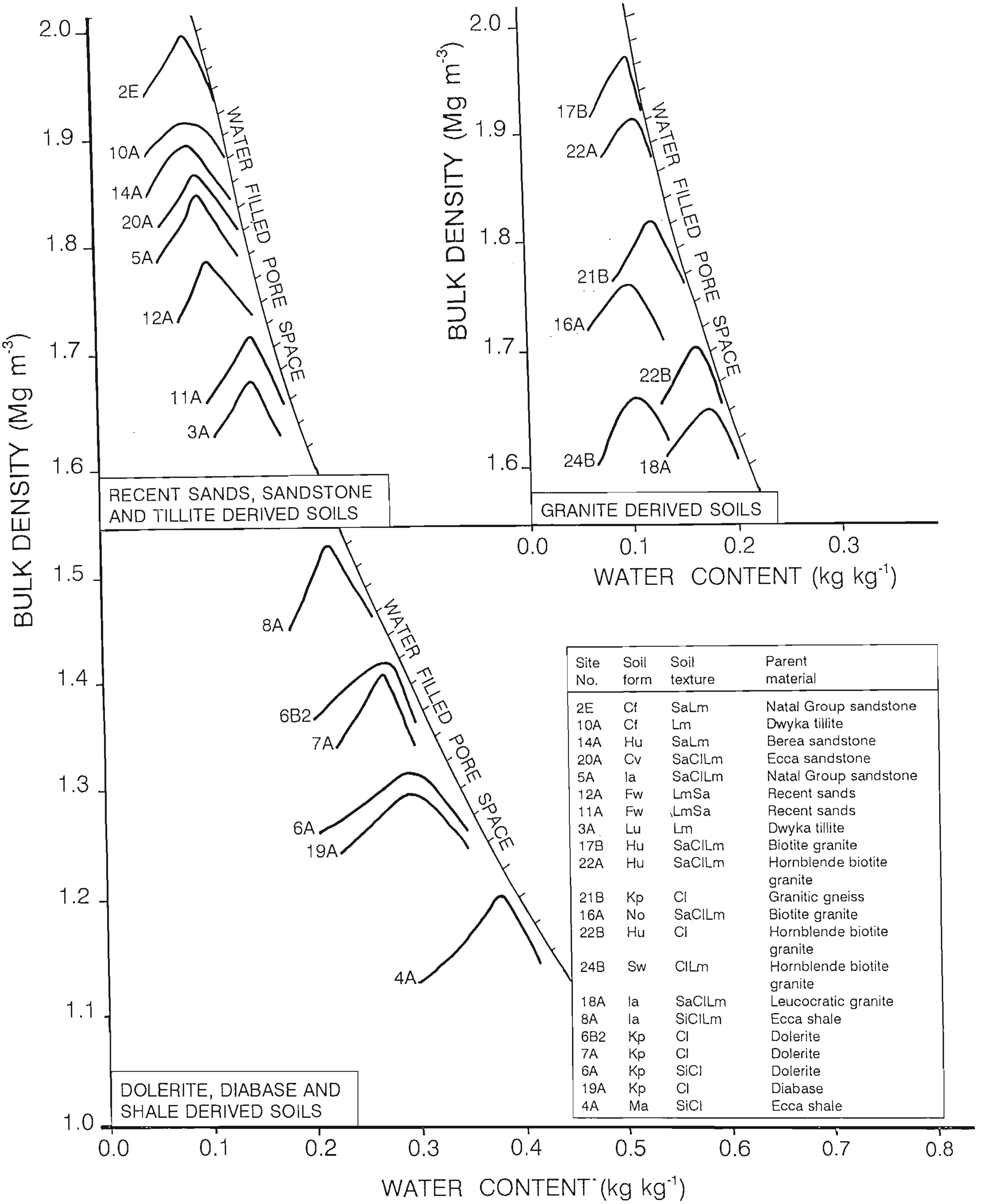
* Dispersable clay

Table 3.2: Partial correlation matrix of relationships between maximum bulk density (MBD), maximum compression index (C_{max}), critical water contents (CWC and CWC_{cmax}) and selected soil physical and chemical properties.

	MBD	CWC	C_{max}	CWC_{cmax}
MBD	1.000 **	-0.921 **	-0.113	-0.882 **
CWC	-0.921 **	1.000 **	0.158	0.929 **
C_{max}	-0.113	0.277 *	1.000 **	0.277
CWC_{cmax}	-0.882 **	0.929 **	0.277	1.000 **
CLAY + SILT	-0.747 **	0.864 **	0.580 **	0.792 **
ORG C (LOI)	-0.879 **	0.941 **	0.285	0.873 **
ORG C (WB)	-0.668 **	0.657 **	0.347 *	0.601 **
CLAY	-0.641 **	0.777 **	0.606 **	0.714 **
FINE SILT	-0.443 **	0.474 **	0.146	-0.500 **
COARSE SILT	-0.644 **	0.699 **	0.415 *	-0.623 **
FINE SAND	0.514 **	-0.682 **	-0.704 **	-0.578 **
MEDIUM SAND	0.635 **	-0.770 **	-0.722 **	-0.656 **
COARSE SAND	0.347 *	-0.247	0.402 *	-0.356 *
KURTOSIS	-0.483 **	0.393 *	-0.571 **	0.493 **
SKEWNESS	-0.706 **	0.844 **	0.615 **	0.764 **
GMD	0.568 **	-0.714 **	-0.802 **	-0.609 **
GSDEV	0.066	0.055	0.650 **	0.006
DISPERSED CLAY	0.300	-0.339 *	0.049	-0.344 *
ECEC	-0.202	0.266	-0.202	0.181

* Denotes r values significant at 0.05 probability level

** Denotes r values significant at 0.01 probability level



Site No.	Soil form	Soil texture	Parent material
2E	Cf	SaLm	Natal Group sandstone
10A	Cf	Lm	Dwyka tillite
14A	Hu	SaLm	Berea sandstone
20A	Cv	SaClLm	Ecca sandstone
5A	Ia	SaClLm	Natal Group sandstone
12A	Fw	LmSa	Recent sands
11A	Fw	LmSa	Recent sands
3A	Lu	Lm	Dwyka tillite
17B	Hu	SaClLm	Biotite granite
22A	Hu	SaClLm	Hornblende biotite granite
21B	Kp	Cl	Granitic gneiss
16A	No	SaClLm	Biotite granite
22B	Hu	Cl	Hornblende biotite granite
24B	Sw	ClLm	Hornblende biotite granite
18A	Ia	SaClLm	Leucocratic granite
8A	Ia	SiClLm	Ecca shale
6B2	Kp	Cl	Dolerite
7A	Kp	Cl	Dolerite
6A	Kp	SiCl	Dolerite
19A	Kp	Cl	Diabase
4A	Ma	SiCl	Ecca shale

Figure 3.1: The relationship between bulk density and water content for selected forestry soils

The extremely low MBD values for humic soils with high clay contents reflect low compactibility and very low natural field bulk density values which in some cases are as low as 0.7 Mg m^{-3} (Musto, 1994). Soils with low MBD values (< 1.4 Mg m^{-3}) are predominantly clays, clay loams, silty clays and silty clay loams with high organic carbon contents (>2.5%) and are derived from base-rich parent materials such as dolerite, diabase, gneiss and shale (Figure 3.1).

Soils with a more even particle size distribution display very high MBD's of greater than 1.80 Mg m^{-3}. These include sandy loams, loams and sandy clay loams derived from sandstone and granites of eastern Transvaal (20A, 17B, 22A, 21B and 16A), tillite and sandstone derived soils of the Natal Midlands (2E, 5A and 10A), and soils derived from sandstone deposits of Zululand (14A). Soils with a high compactibility (1.6 Mg m^{-3} to 1.8 Mg m^{-3}) include the sandy soils of Zululand (11A and 12A) and sandy clay loams of granite derived soils (18A, 24B and 22B). In some cases moderate organic carbon contents (>1.5%) appear to have the effect of depressing MBD for soils of these textural classes (e.g. 3A and 18A). However, it is of interest to note that the Inanda sandy clay loam (5A) derived from Natal Group sandstone, which possesses a humic topsoil (organic carbon (WB) = 2.15%), still achieved a remarkably high MBD of 1.84 Mg m^{-3}.

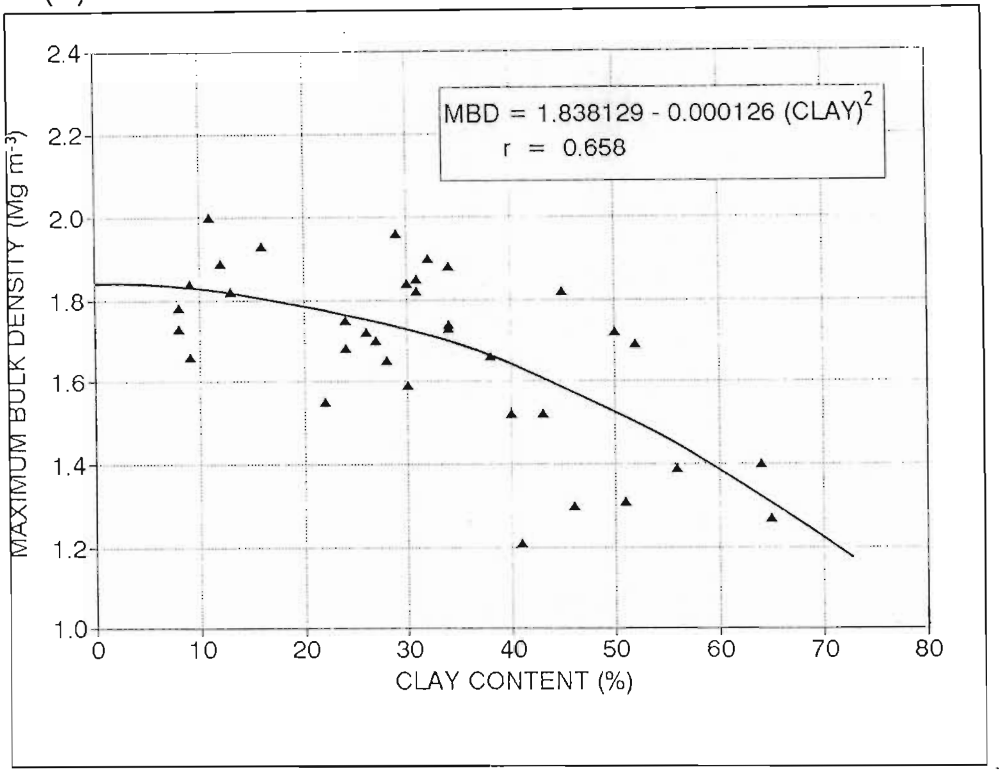
The results in Table 3.2 show that clay plus silt, clay, coarse silt, fine silt, medium sand and fine sand were all significantly correlated with MBD. The increase in MBD as fine silt decreases is in accordance with the results of Heinonen (1977). Clay percentage was significantly correlated with MBD, the regression improving slightly from $r = -0.641$ to $r = 0.658$ by using the square of the clay content (Figure 3.2a). These are similar to the results of Heinonen (1977) and Henning *et al.* (1986). The latter reported increasing MBD with increasing clay content up to about 20% clay and then decreased with increasing clay content. On the other hand, Van Huyssteen (1989) found no correlation between the two properties.

The effect of decreasing MBD with increasing clay plus silt content has been noted by other authors (Van Der Watt, 1969; Van Wambeke, 1974; Van Huyssteen, 1989). The linear correlation presented in Table 3.2 has been improved by including a squared term in the regression equation (Figure 3.2b). Inspection of Figure 3.2b shows that MBD increases up to about 25% clay plus silt and then decreases again. It is interesting to note that Moolman (1981) found that increasing clay plus silt resulted in progressively higher MBD values for soils with less than 40% clay plus silt. Similarly, in the absence of soils with over 20% silt plus clay, Bennie and Burger (1988) found a positive correlation between clay plus silt and MBD. Figure 3.2b shows that the highest maximum bulk densities would be between 15 and 35% silt plus clay. It should be noted that sandy soils did not compact to high bulk densities under the conditions of the Proctor test. Soils with large sand:clay ratios will compact to higher densities under vibration rather than static or impact loading tests (Basma and Tuncer, 1992).

Significant relationships were found between all sand grades and MBD (Table 3.2). The significant relationship between coarse sand and MBD, though weak (see Table 3.2) was similar to the results of Van Der Watt (1969) and Van Huyssteen (1989). This result is consistent with the aforementioned literature despite the changes in particle size limits made by the Soil Classification Working Group (1991) as coarse sand particle sizes remained the same (0.5 to 2.0 mm; see Appendix 5). Fine and medium sand were both significantly correlated with MBD (Table 3.2) and indicated that increasing fine sand and medium sand resulted in higher MBD values. However, consideration of the scatter plots of the relationship between MBD and either fine sand or medium sand (Figure 3.2c and d) shows a quadratic relationship. MBD increases with increasing fine or medium sand up to a point and then decreases again. The addition of a squared term into the regression equation improves the correlation coefficient from $r = 0.514$ to $R = 0.607$ for the relationship between fine sand and MBD, and from $r = 0.635$ to $R = 0.755$ for the relationship between medium sand and MBD (Table 3.2 and Figure 3.2c and d). Although the results are not presented here, it is of interest to note that considering medium sand **plus** fine sand as a single independent variable did not improve the correlation with MBD over the correlation with either fine sand or medium sand.

Although the results given here indicate that MBD may be adequately predicted by fine sand, they do not confirm the general opinion in forestry propagated by Grey *et al.* (1987) that higher fine sand contents result in higher compactibility. Due to the changes in particle size limits for fine sand (Soil Classification Working Group, 1991) agreement between MBD and pre- and post-1991 fine sand would, in any case, be slightly fortuitous since some of the previous fine sand particle size class (0.02 to 0.2 mm) now belongs to the new coarse silt size class (0.02 to 0.05 mm; see Appendix 5). It is of interest to note that coarse silt was significantly negatively correlated to MBD (Table 3.2).

(a)



(b)

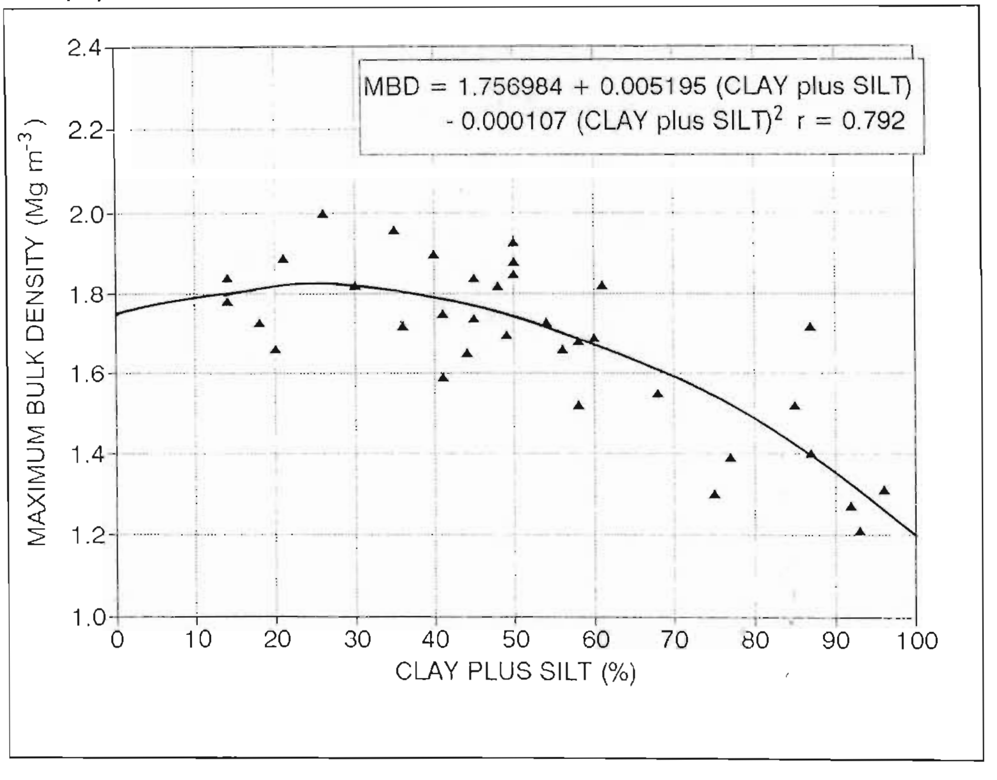
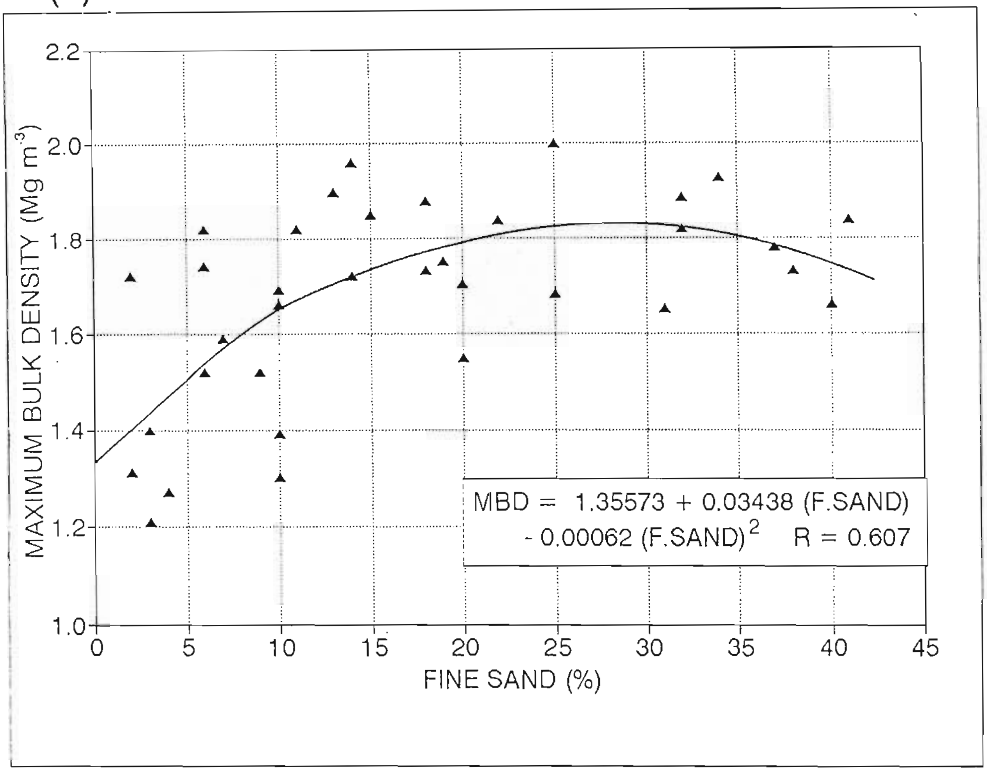


Figure 3.2: Relationship between MBD and (a) clay content, (b) clay plus silt content, (c) fine sand content, (d) medium sand content, (e) geometric mean diameter (GMD), (f) skewness, (g) organic carbon (LOI) content and (h) organic carbon (WB) content.

(c)



(d)

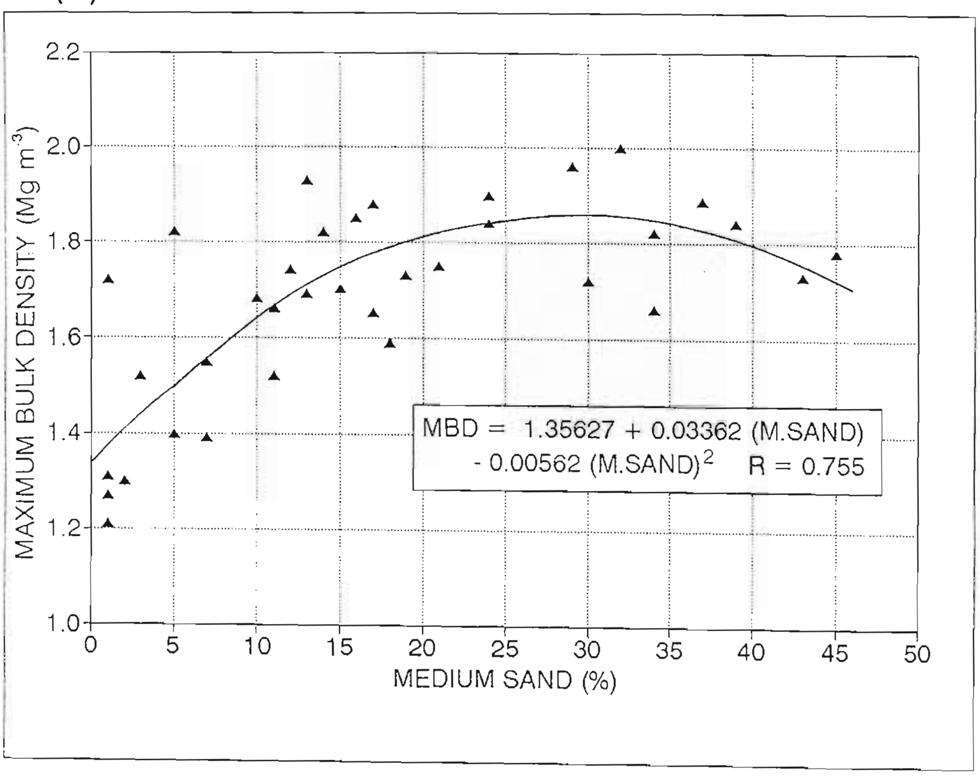
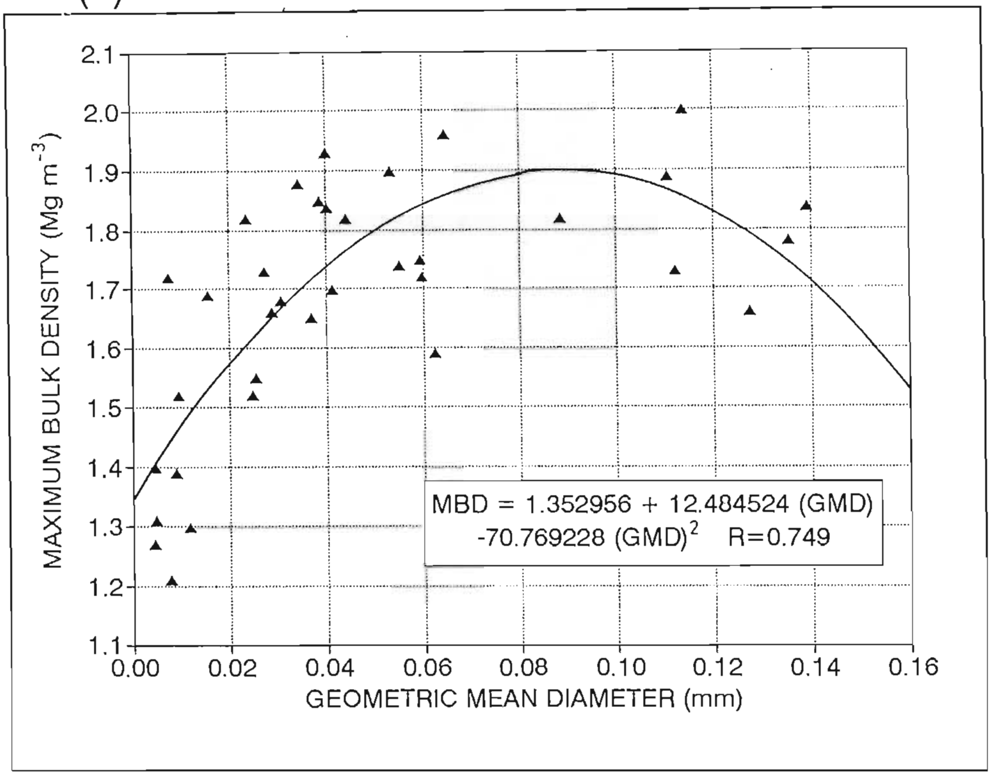


Figure 3.2: (continued)

(e)



(f)

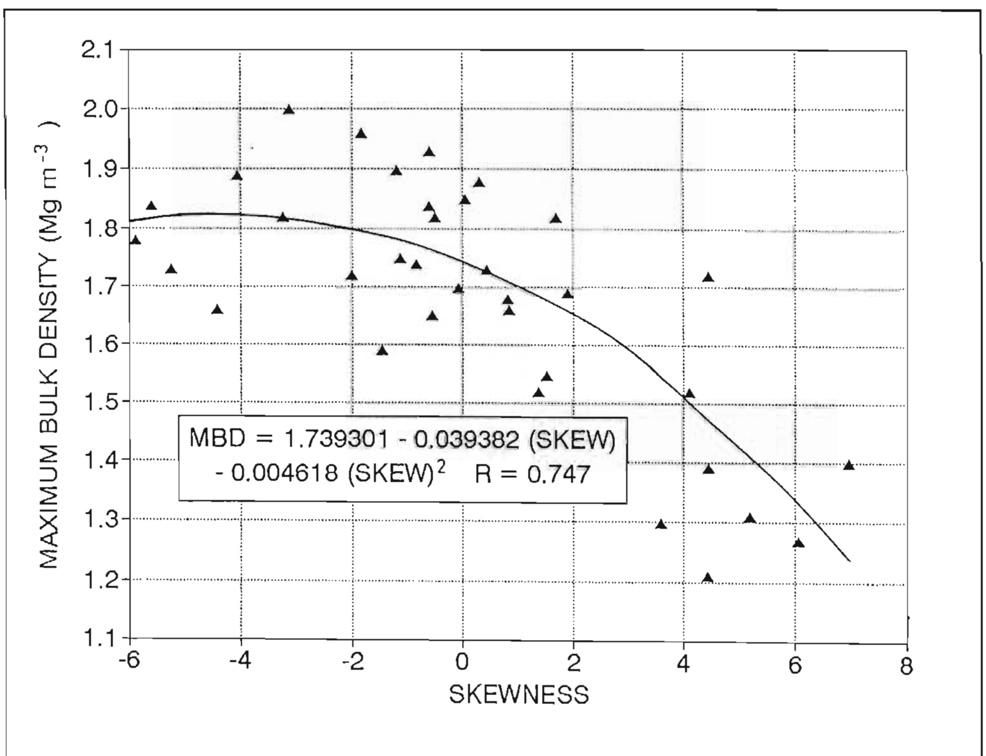
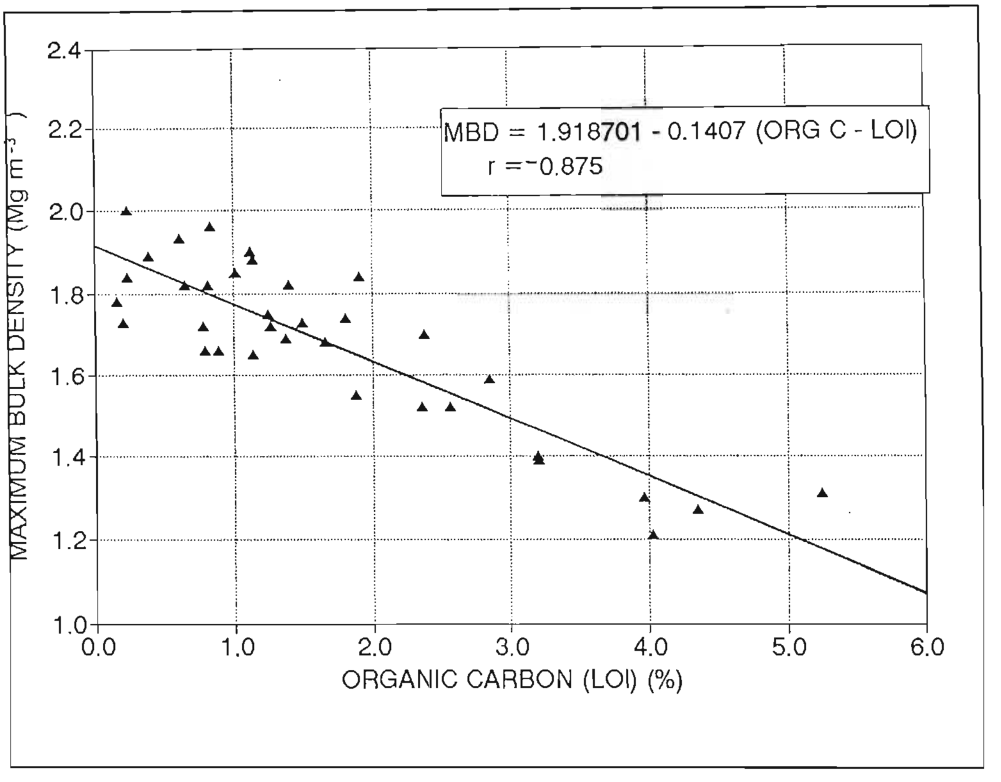


Figure 3.2: (continued)

(g)



(h)

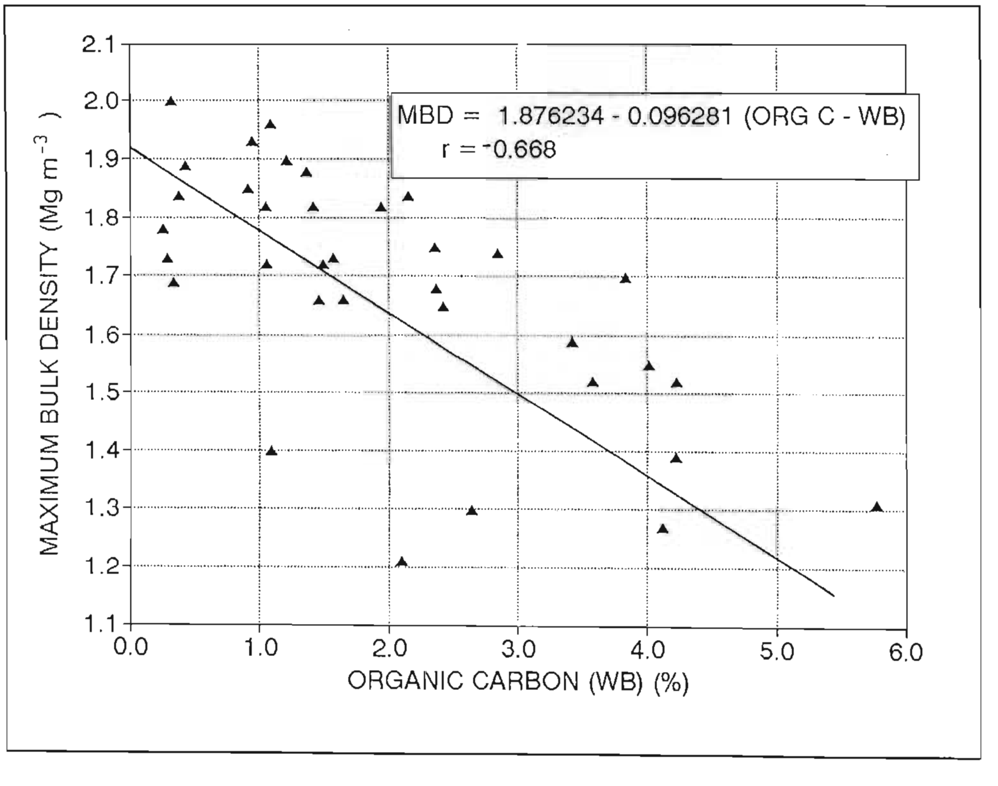


Figure 3.2: (continued)

3.3.2 Compactibility and other measures of particle size distribution

Although most relationships between various particle sizes and MBD were significant, substantial covariance existed between the various particle sizes (Appendix 4). Coarse silt, for example, is significantly correlated to all the other particle sizes except coarse sand. Utilising measures of grading of the particle sizes such as geometric mean diameter (GMD), geometric standard deviation (GSDEV) (Shirazi and Boersma, 1984), kurtosis and skewness should provide an overall view of the effect of texture on MBD.

Inspection of Table 3.1 reveals that values for kurtosis range from -3.574 to 3.991 and for skewness from -5.884 for sandy soils to 6.96 for clay soils. Webster (1979) has noted that for normal distributions, skewness has a value of 0 and kurtosis has a value of 3. High coefficients of kurtosis indicate that the majority of particles are concentrated into a small number of adjacent particle sizes. The lower the coefficient of kurtosis the more even the particle size distribution. This explains why, for example, soils with very high clay plus silt values **and** soils with high sand contents both displayed high kurtosis values, i.e. a strong degree of peakedness reflecting the concentration of particle sizes within one or two adjacent particle size categories (see Table 2.2). Soils with negative kurtosis values were those which displayed no peakedness at all and possessed particle sizes dominated by clayey and sand particles with few silt particles. In other words, a dip occurs in the frequency distribution diagram rather than a peak. This is commonly the case with soils derived from granite (16A to 26A with the exception of 19A; Table 3.1 and cross-reference with Table 2.1).

MBD decreased as the degree of peakedness of particle size distribution increased, i.e. a tendency to have a very high frequency of one class (Table 3.1). This is in accordance with the results of Moolman (1981) and Van Huyssteen (1989). Although, in this study, a significant relationship was found between MBD and kurtosis (Table 3.2), the correlation was not as strong as that of Moolman (1981) who found kurtosis to be the most important factor influencing compactibility, explaining 82% of the variation in MBD. The fact that the correlation was not so strong in this study was perhaps not entirely unexpected since soils with similar kurtosis do not necessarily have similar particle size distributions, e.g. sands and clays, and therefore MBD's. In addition, a wide range of soil textures and organic carbon contents of the soils was studied here. As will be seen in the following section organic carbon was well correlated with MBD and therefore may confound the simple relationship between kurtosis, which is essentially a measure of the grading of the particle sizes, and MBD. It is unfortunate that the organic matter contents of the soils used by Moolman

(1981) were not recorded but it is likely that as the soils were sampled from intensively managed crop production areas in the southern and western Cape that organic matter contents were low and that this fact, in addition to the relatively low clay plus silt contents (<50%), contributed to the strong correlation in that study between kurtosis and MBD.

Consideration of the preceding factors possibly also contributed to the lack of any significant relationship between GSDEV and MBD which was surprising since GSDEV is a measure of the grading of the particle sizes. It is interesting to note that normalising the kurtosis values with respect to GMD (kurtosis/GMD) had the effect of improving the correlation between kurtosis and MBD. The correlation coefficient of r = -0.483 (Table 3.2) for the relationship between MBD and kurtosis was improved to -0.583 following normalisation.

Table 3.2 shows that significant relationships were found between GMD and MBD on the one hand and skewness and MBD on the other. Both of these correlations were improved substantially by the addition of a squared term into the regression equation (Figure 3.2e and f), indicating that the relationships are quadratic rather than linear. The correlation between MBD and skewness essentially mirrored the relationship between MBD and clay plus silt (Figure 3.2b). This would be expected since soils which have a high proportion of large particle sizes, e.g. sands (low clay plus silt), have a negatively skewed particle size distribution and those possessing a high proportion of small particle sizes, e.g. clays (high clay plus silt), have a positively skewed particle size distribution. Inspection of the relationship between clay plus silt and skewness (Appendix 4) reveals a high degree of covariance (r = 0.98). These results differ slightly from the results of Moolman (1981) and Van Huyssteen (1989) who reported no relationship between MBD and skewness alone. These authors excluded skewness from the final regression model predicting MBD, not because there was no relationship *per se* but due to elimination during the step-wise regression procedure.

3.3.3 Compactibility and organic carbon

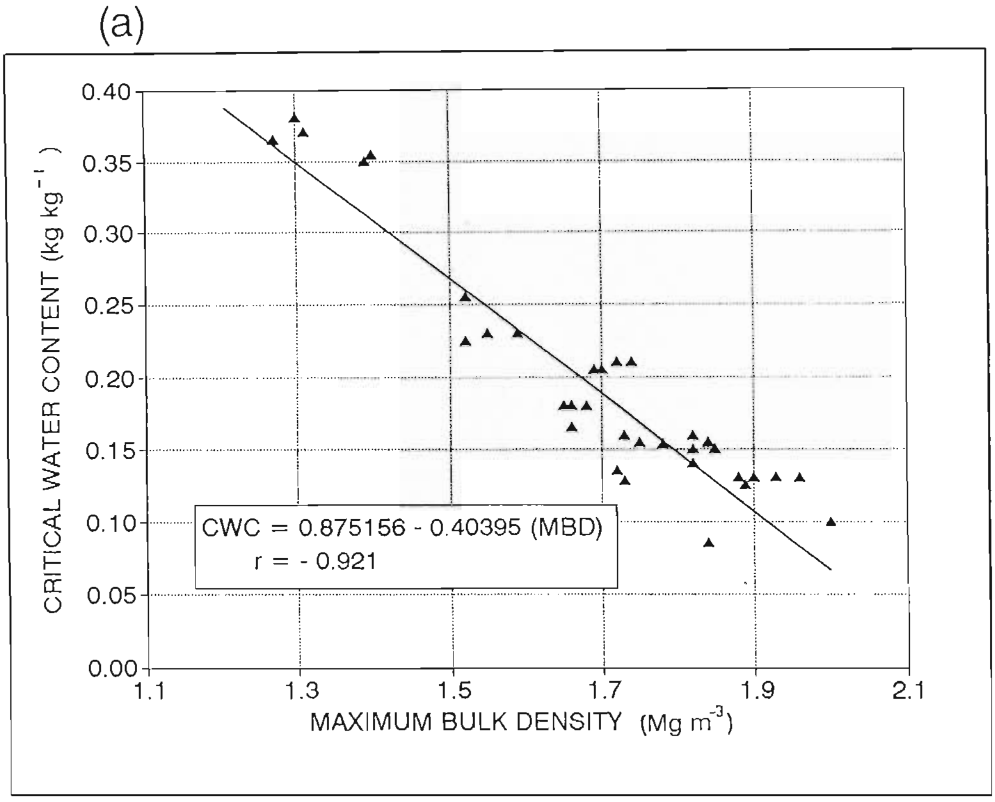
MBD was significantly correlated with organic carbon as determined by loss-on-ignition (LOI) (Table 3.2 and Figure 3.2g). This is a very useful relationship as this property is relatively easy to determine in the laboratory. The slightly better correlation between MBD and organic carbon (LOI) than between MBD and either clay plus silt or organic carbon (WB) (Figure 3.2b and h respectively) could be due to the fact that loss-on-ignition may include a structural water component which is lost during ignition to 450°C especially on more finely textured soils (Donkin, 1991). Thus LOI organic carbon is a reflection of both organic carbon and clay plus silt. This result is opposite to that of Howard *et al.* (1981) who showed that percent organic carbon by the Walkley-Black method had a better correlation with MBD than loss-on-ignition.

An explanation for the good correlations between organic carbon (both LOI and WB) and compactibility could be the wide range of organic matter levels found in forestry soils in this study and the degree to which organic carbon is covariate with clay plus silt (Appendix 4). Studies in which a wide range of organic matter levels characterised the sample population also found close relationships between organic matter and compactibility (Howard *et al.*, 1981). Alexander, (1980) found organic carbon to be one of the most important variables in predicting bulk density of upland and alluvial soils in California.

Although good correlations between MBD and organic carbon content were established it is not clear whether organic carbon affected MBD *per se* or the relationships simply reflected the covariance between silt plus clay and organic carbon (Appendix 4). The various measures of particle size distribution (GMD, skewness and clay plus silt), consistently showed better relationships with MBD than did organic carbon (WB). It is suggested that the development of MBD in forestry soils is primarily related to soil texture but is affected to a certain extent by organic matter. This view is corroborated by the very good correlations achieved between MBD and organic carbon as measured by loss-on-ignition which, although primarily a measure of organic carbon, may also include a structural water component thus reflecting soil texture.

3.3.4 Critical water content (CWC)

CWC was significantly correlated with MBD (Figure 3.3a), clay plus silt (Figure 3.3b), and LOI organic carbon (Figure 3.3c). These results are in general agreement with those of De Kimpe *et al.* (1982) and Van Huyssteen (1989) and can be attributed to the co-variance between water holding capacity and soil texture and organic carbon. Similarly, significant relationships were also found between CWC and GMD (Figure 3.3d), organic carbon (WB), and skewness (Table 3.2).



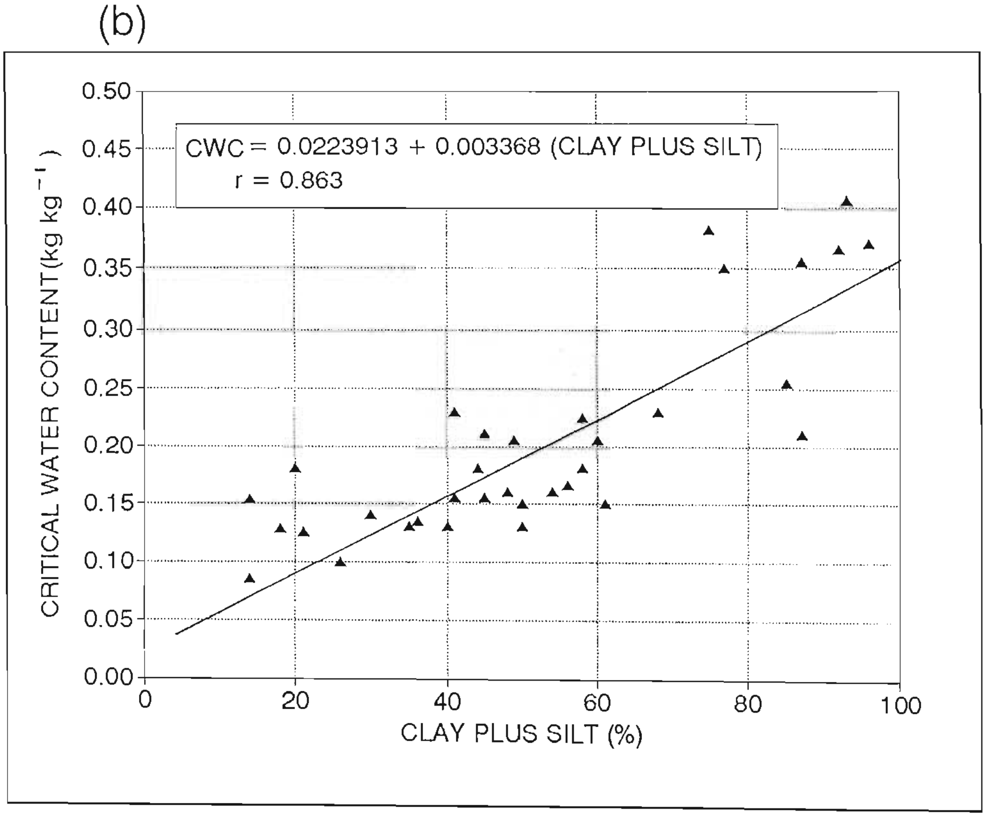
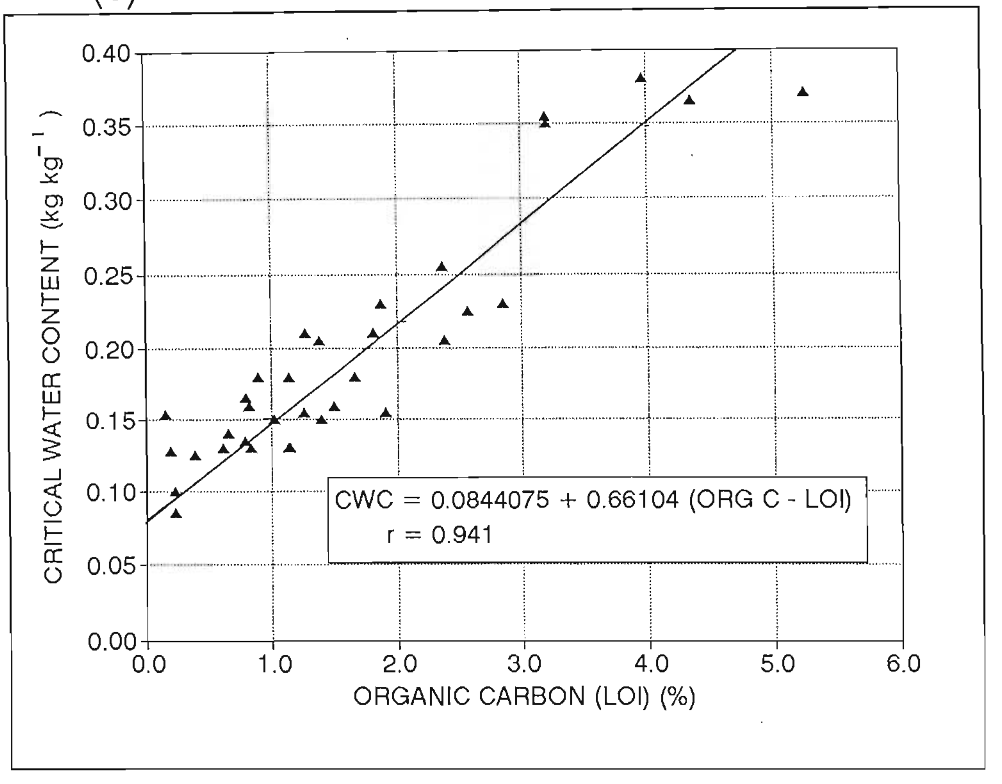


Figure 3.3: Relationship between critical water content (CWC) and (a) maximum bulk density MBD, (b) clay plus silt content, (c) organic carbon (LOI) content and (d) geometric mean diameter (GMD).

(c)



(d)

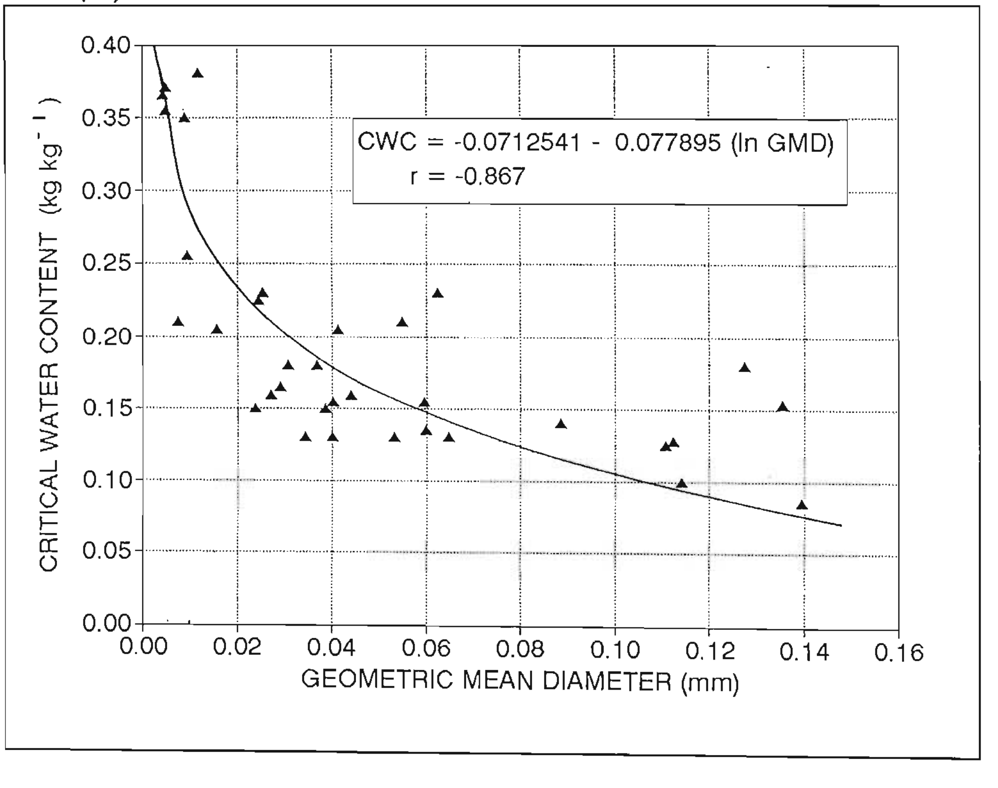


Figure 3.3: (continued)

3.3.5 Factors influencing maximum soil compressibility (C_{max})

Values of C_{max} range from about 0.1 for relatively incompressible loamy sands with low organic carbon contents to about 0.6 for clay soils (Table 3.1). This range is similar to that reported by Larson *et al.* (1980) and Gupta and Allmaras (1987) for soils from seven orders of Soil Taxonomy (Soil Survey Staff, 1990), and Saini *et al.* (1984) who reported compression index values between 0.153 and 0.245 for a range of soil textures.

Table 3.2 shows that C_{max} was linearly correlated with clay, clay plus silt, fine and medium sand, GMD, GSDEV, skewness and kurtosis. Although no significant linear correlation was noted between C_{max} with organic carbon (LOI), introduction of a squared term resulted in a significant quadratic relationship (Figure 3.4a). The highly significant relationship between clay content and C_{max} (Figure 3.4b) was similar to the results of Gupta and Allmaras, (1987) who presented a similar quadratic equation. The contention of Larson *et al.* (1980) that *C* values would be approximately constant above 33% clay as soils are essentially a clay matrix with coarser material embedded in the clay is not supported by the data presented here. C_{max} values continue rising up to 0.6 at a clay content of approximately 50%. This clearly demonstrates that very different compression behaviour occurs at higher clay contents. A distinct group of four "outliers" with clay contents above 40% and C_{max} values of less than 0.45 occurs below the central portion of the regression line in Figure 3.4b. Taking these four points out of the regression equation markedly improves R of the relationship between C_{max} and clay content from 0.862 to 0.964 using a similar quadratic model. Inspection of the data in Table 2.2 reveals that these four soils (4A, 6A, 6B and 6B2) have very high silt contents of between 23 and 52%. This indicates the role of silt in affecting the compressibility of soils and shows why the correlation between C_{max} and clay was improved markedly when silt content was considered together with clay as an independent variable (i.e. clay plus silt). C_{max} was particularly well predicted by clay plus silt (Figure 3.4c) and skewness (Figure 3.4d). Once again this draws attention to the high degree of covariance between skewness and clay plus silt percentage (Appendix 4). Figure 3.4c illustrates that C_{max} values are highest when clay plus silt contents are between 50 and 80% and then decrease again over 80% clay plus silt.

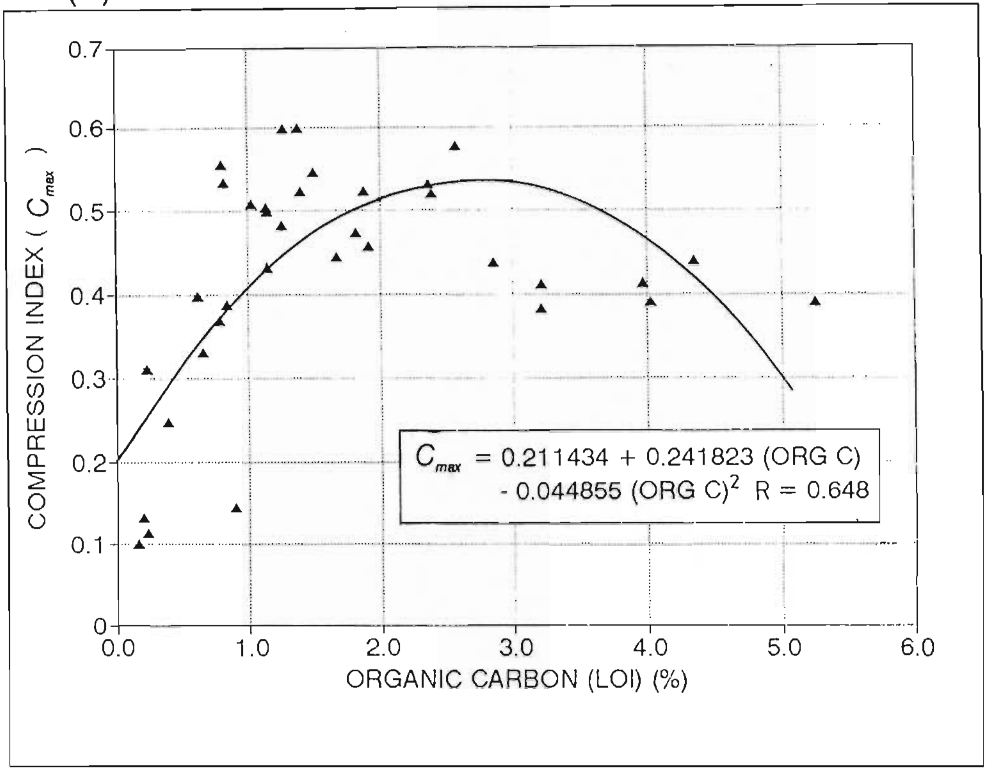
A possible explanation for the changes in compressibility with increasing clay plus silt are as follows. For the coarser textured soils (less than 30% clay plus silt) initial bulk densities are high relative to MBD and frictional forces dominate the soils' resistance to compression and thus compressibility is low. Increasing clay content reduces the magnitude of the frictional forces resisting compression and soils, combined with an increase in porosity, are more likely to undergo volume reduction for an increment of applied pressure. Compressibility becomes a maximum at clay plus silt contents of between 55 to 70% (Figure 3.4c) or clay contents of between 35 and 50% (Figure 3.4b). Compressibility declines at higher clay contents. This is probably related to the pore size distribution of the more finely textured soils being dominated by the smaller pore sizes and, lacking an even distribution of particle sizes, soil particles are not forced together as easily.

The high correlations achieved between C_{max} and textural parameters (clay, clay plus silt, skewness, GMD and GSDEV; Table 3.2 and Figure 3.4 (b-f)) compared to the poorer correlations noted between C_{max} and LOI and WB organic carbon (Figure 3.4a and Table 3.2, respectively), indicate that soil texture is overriding in its influence on compressibility of forestry soils. This impression is reinforced when one considers that three soils which have high organic carbon (WB) contents, i.e 21A, (4.23%), 1A (4.02%) and 8A (3.58%), have some of the highest C_{max} values, (0.577, 0.523 and 0.531 respectively). Also, the weak linear correlation with WB organic carbon (Table 3.2) could not be improved by transformation or introduction of power terms into the regression whereas LOI organic carbon was a better predictor of C_{max}. The better correlation obtained between C_{max} and LOI organic carbon rather than with WB organic carbon probably reflects in part a clay plus silt component in the LOI organic carbon measurement (Donkin, 1991). In this respect the strong co-variance between silt plus clay and LOI organic carbon is notable (Appendix 4).

It is believed that the greater effect of particle size distribution over organic matter on the compressibility for soils in this study could be explained by the spatial arrangement of mineral and organic particles. Because the finer textured soils possess a relatively high specific surface area the amount of organic matter in the soils of this study was not enough to interfere with the mineral particle interfaces sufficiently to hinder compression. It has been shown that even large additions of crop residues to natural soils were not enough to appreciably affect the compression index of soils of varying textures (Gupta *et al.,* 1987). It is suggested that a clearer understanding of the mechanics of the mineral:organic interface is a pre-requisite for defining more precisely the role of organic carbon in the compaction process.

There is no paradox that soils which are highly compactible (high MBD) may be relatively incompressible. For example, sandy soils possess a high bearing capacity (low compressibility) but are highly compactible in terms of attainment of a relatively high maximum bulk density. Part of the reason for this is that natural bulk densities of sands are high. Clayey soils, other than those with very high clay plus silt values, are highly compressible which simply means that they undergo larger changes in the air-water-soil matrix than sandy soils for a given increment of applied pressure (Gupta and Allmaras, 1987) mainly due to their higher initial porosity.

(a)



(b)

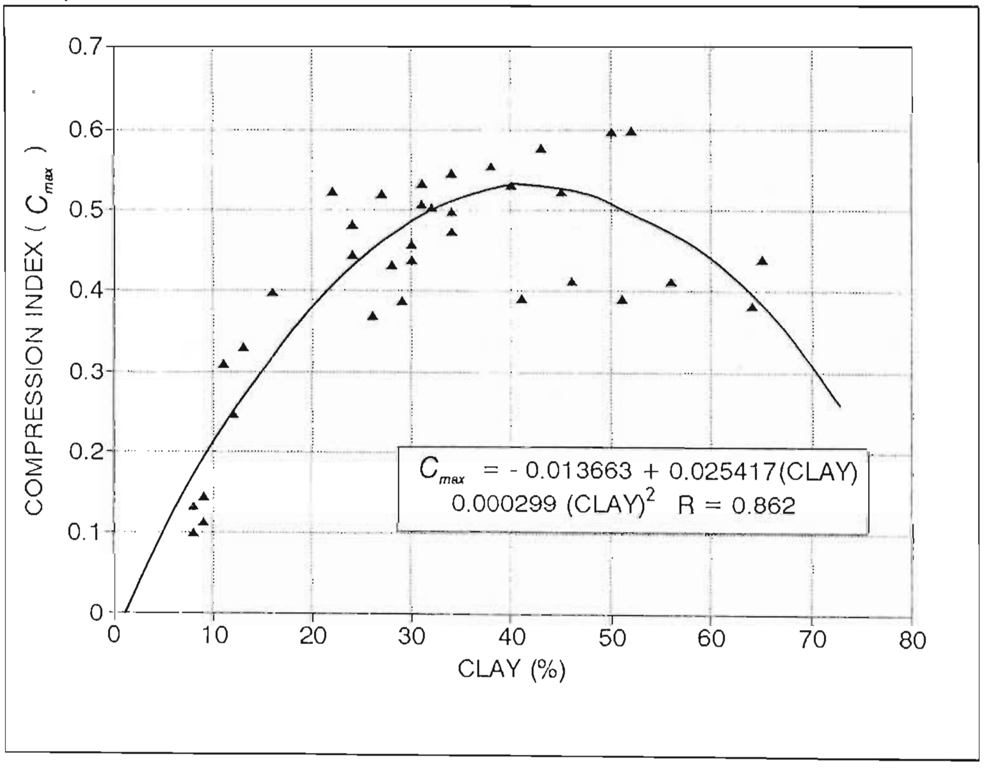
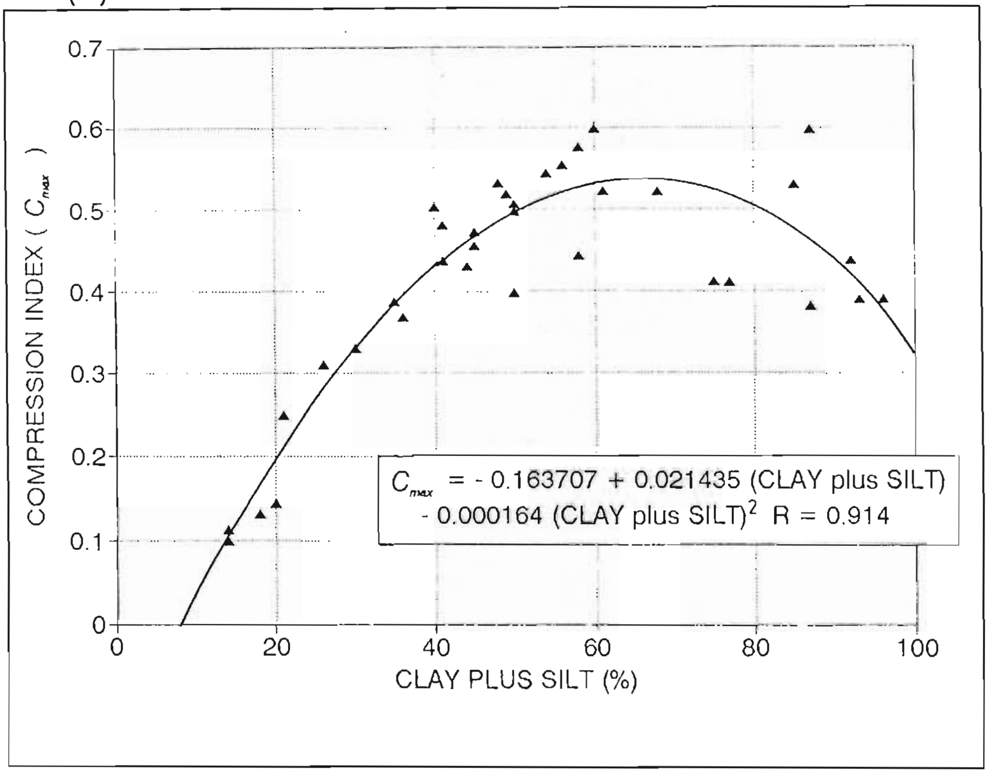


Figure 3.4: Relationship between C_{max} and (a) organic carbon (LOI) content, (b) clay content, (c) clay plus silt content, (d) skewness, (e) geometric mean diameter (GMD) and (f) geometric standard deviation (GSDEV).

(c)



(d)

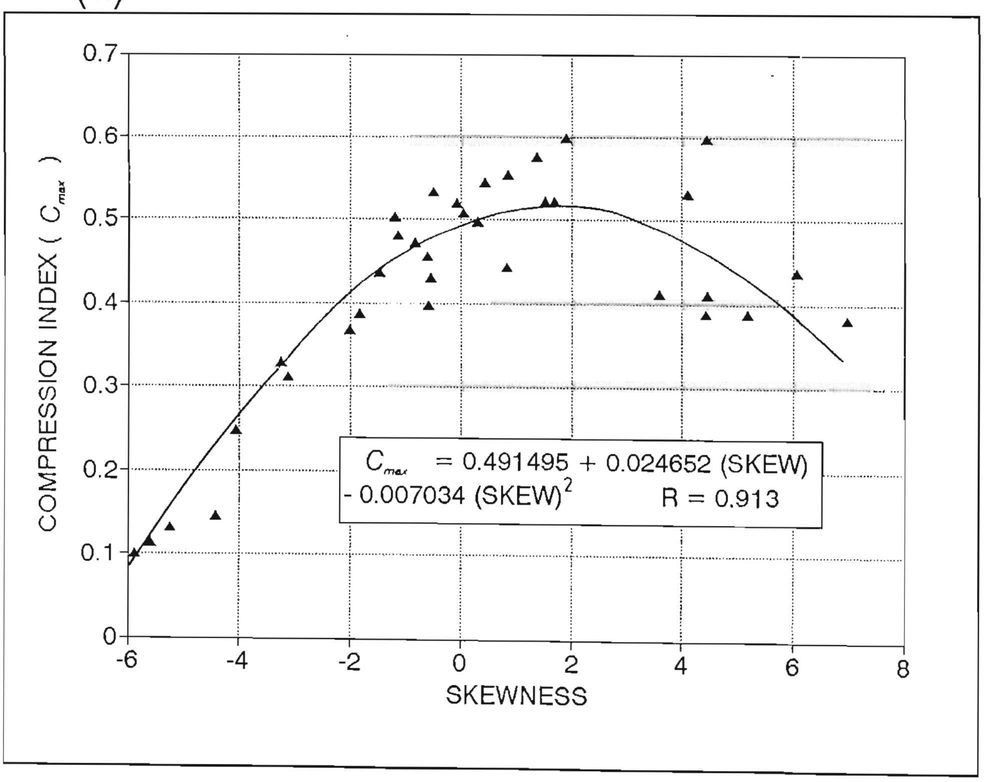
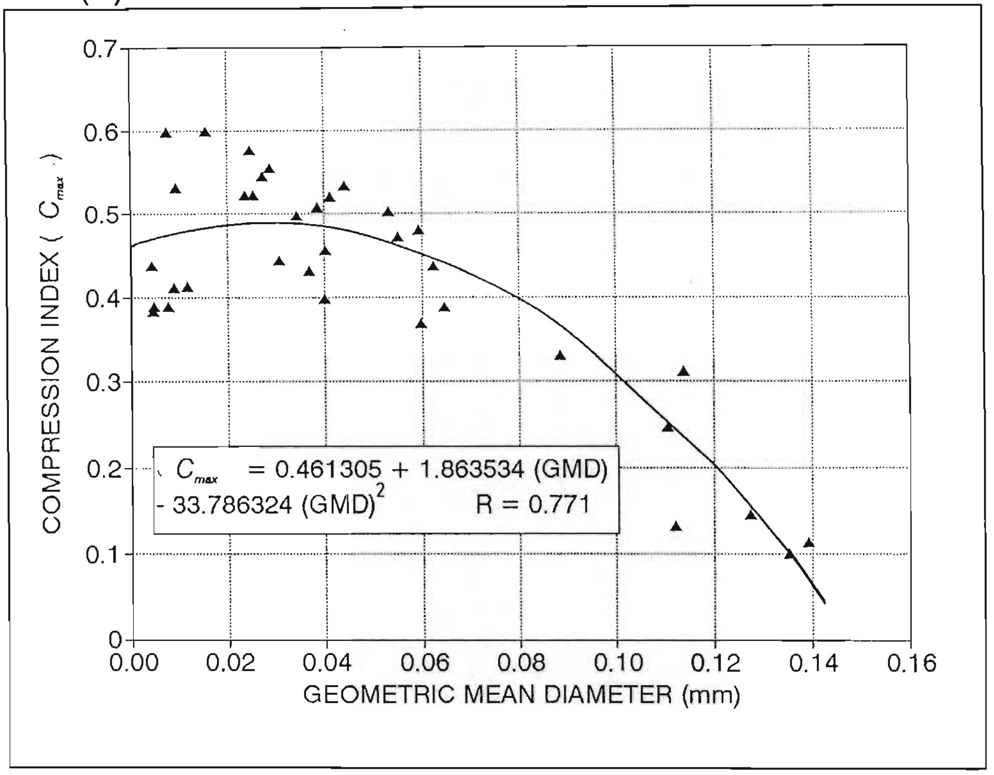


Figure 3.4: (continued)

(e)



(f)

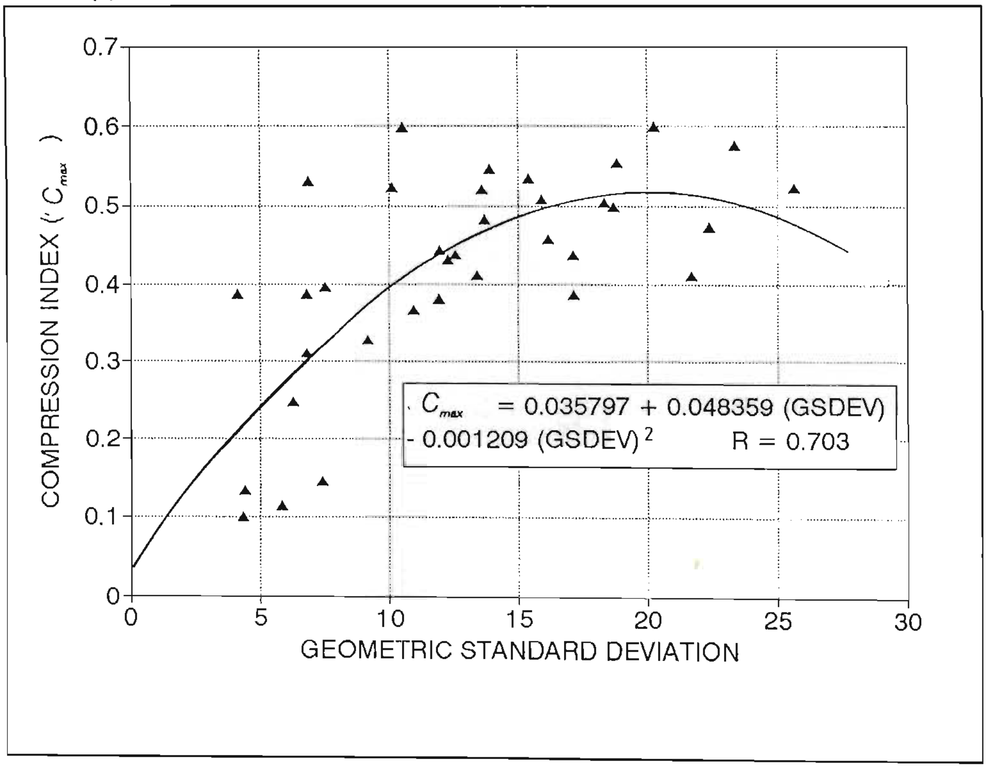


Figure 3.4: (continued)

3.3.6 Use of the Gupta model in predicting C values of South African forestry soils

As Gupta and Allmaras (1987) presented models for application to world soils, a model validation test was carried out to evaluate the effectiveness of this model in predicting C_{mod} and C_{max} for South African forestry soils which included Oxisols, Ultisols, Alfisols as well as Inceptisols and Entisols. Compression indices were calculated from the models of Gupta and Allmaras (1987) for Oxisols, Ultisols and Alfisols from Equation 3.3 and for Entisols and Inceptisols by Equation 3.4 and compared with both C_{mod} and C_{max} data in Tables 2.4 and 3.1.

$$C = 0.2148 + 0.01203(\text{Clay}) - 0.0001161(\text{Clay})^2 \qquad [3.3]$$

$$C = 0.2085 + 0.01441(\text{Clay}) - 0.0001494(\text{Clay})^2 \qquad [3.4]$$

The method used to evaluate the models was similar to that proposed by Willmott (1982). This involved calculating the root mean square error (RMSE) and separating the RMSE into systematic ($RMSE_s$) and unsystematic ($RMSE_u$) components which describe the performance of the model (Equations 3.5, 3.6 and 3.7). The $RMSE_u$ quantifies the bias or the departure of the observed relationship from the 1:1 relationship, whereas $RMSE_s$ describes the random variation of the observed data from the predicted mean.

$$RMSE_s = [n^{-1} \sum_{n}^{i=1} (P\hat{} - O)^2]^{0.5} \qquad [3.5]$$

$$RMSE_u = [n^{-1} \sum_{n}^{i=1} (P_i - P\hat{})^2]^{0.5} \qquad [3.6]$$

$$RMSE^2 = RMSE_s^2 + RMSE_u^2 \qquad [3.7]$$

where $P\hat{}$ is the predicted value of the model, P_i is the observed (actual data) value and O the observed value as predicted from the regression between predicted and measured values. Willmott (1982) has suggested that with a "good" model the systematic error ($RMSE_s$) should approach zero while the unsystematic ($RMSE_u$) should approach the total RMSE which should be low. The statistical evaluation for measured versus predicted values for both C_{mod} and C_{max} are presented in Table 3.3 and Figure 3.5a and b.

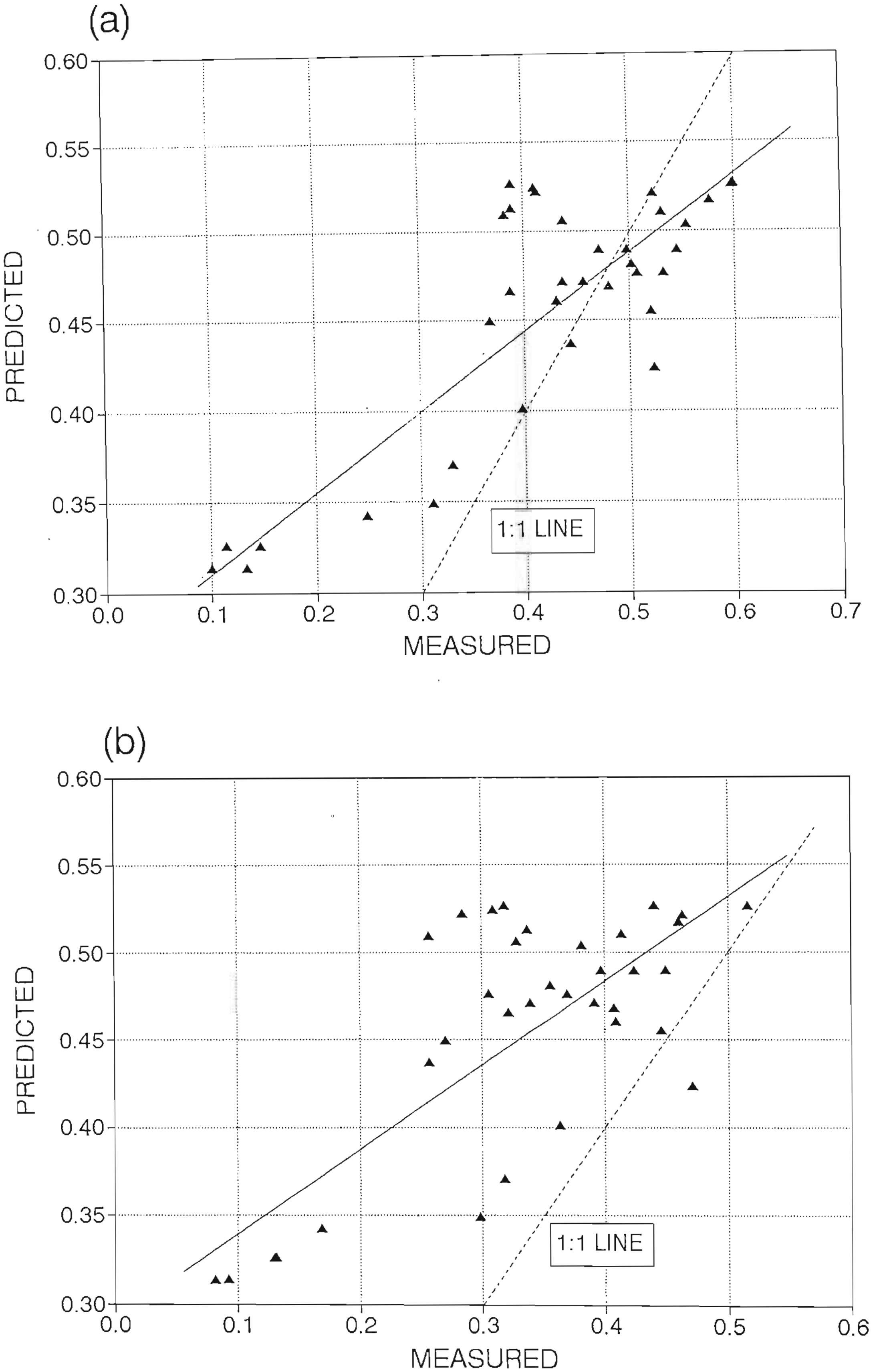


Figure 3.5: Comparison of predicted (Gupta model) versus measured values of (a) C_{max} and (b) C_{mod}. Solid lines indicate the regression of predicted against measured (see Table 3.3).

Table 3.3: Relationship between predicted (dependent variable) and measured compression indices C_{mod} and C_{max} using the model of Gupta and Allmaras (1987).

Variable	Slope	Intercept	r	n	S.E.E.*	RMSE		
						TOTAL	$RMSE_s$	$RMSE_u$
C_{mod}	0.4518	0.3048	0.72**	35	0.0483	0.1507	0.0469	0.1433
C_{max}	0.4223	0.2786	0.83**	35	0.0392	0.1006	0.0381	0.0931

* Standard error of predicted compression index
** Indicates significant at the 1% probability level

The results show that for both C_{mod} and C_{max} the bias was low but that the random error was large (Table 3.3). However, the bias and random error were larger for C_{mod} than for C_{max} indicating that the models did not predict C_{mod} as well as C_{max}. This is also evident by inspection of Figure 3.5b where it can be seen that the models generally overpredicted C_{mod} which amounted to 0.1 unit in general and slightly more for the coarsely textured soils. This is possibly due to the inclusion of the compression lines of relatively dry samples with low *C* values in the calculation of C_{mod} (see Section 2.3.2). According to Larson *et al.* (1980), whose data Gupta and Allmaras (1987) utilised in part to derive Equations 3.3 and 3.4, the lowest soil water contents corresponded to a matric potential of approximately -100 kPa. Some of the soils in this study were considerably drier than this during the compression testing. This point is reinforced by consideration of C_{max} which is better predicted by the models and shows less bias and random error than C_{mod} (Table 3.3 and Figure 3.5). Because maximum compressibility usually corresponded to higher soil water contents during compression, the measurement of C_{max} rather than C_{mod} compared better with the test conditions of Larson *et al.* (1980). From a practical standpoint, the fact South African forestry soils are fairly dry for much of the year would suggest that the Gupta models have limited application in the prediction of C_{mod} for modelling compaction behaviour. However, the better agreement between the models and C_{max} indicate that the models can successfully compare compressibility of soils of varying soil textures and therefore provide a first approximation in establishing compaction susceptibility.

3.3.7 Critical water content (CWC_{cmax})

CWC_{cmax} represents the water content at which the compression curve (slope = C) is steepest for a plot of bulk density against applied pressure. The relationship between compression index and water content is illustrated in Figure 3.6 for four soils, 22A, 18A, 3A and 5A. In many respects the graphs reflect the bulk density - water content relationship for calculating CWC at MBD. Relating the gravimetric water contents in Figure 3.6 with matric potential from the water retentivity curves in Figures 5.2 (Chapter 5) shows that CWC_{cmax} occurs at water contents corresponding to matric potentials of between -33 and -100 kPa. The exceptions to this are the sandy soils which undergo maximum compression between field capacity (-10 kPa) and saturation or when they are close to wilting point.

CWC_{cmax} was significantly correlated with every soil physical property except GSDEV and C_{max} (Table 3.2) and a particularly highly significant relationship was noted between CWC_{cmax} and LOI organic carbon content (Figure 3.7b). In contrast to the relationship reported earlier between CWC and MBD, no correlation was noted between CWC_{cmax} and C_{max}. It is interesting to note that a highly significant linear relationship existed between CWC (at MBD) and CWC_{cmax} (Figure 3.7a). In general CWC was greater than CWC_{cmax} and would indicate that the short duration uniaxial compression technique is more effective in compacting the soils than the impact method.

3.3.8 Relationship between MBD, C_{max} and ECEC and Dispersible Clay

ECEC was included in the correlation analysis as it has been shown to be strongly corrleted with climatic indices and therefore tree growth potential for Natal forestry soils (Donkin and Fey, 1993). However, Table 3.2 shows that no significant relationship existed between ECEC and MBD or C_{max}.

A number of authors have recommended the use of dispersible clay as a measure of soil structural condition (Shanmugunathan and Oades, 1982; Rengasamy *et al.,* 1984). As such it was hypothesised that it may be related to compressibility or compactibility. The lack of any relationship between indices of compaction and dispersible clay (Table 3.2) are similar to the results of Van Huyssteen (1989) who found that compaction processes were not necessarily associated with structural stability.

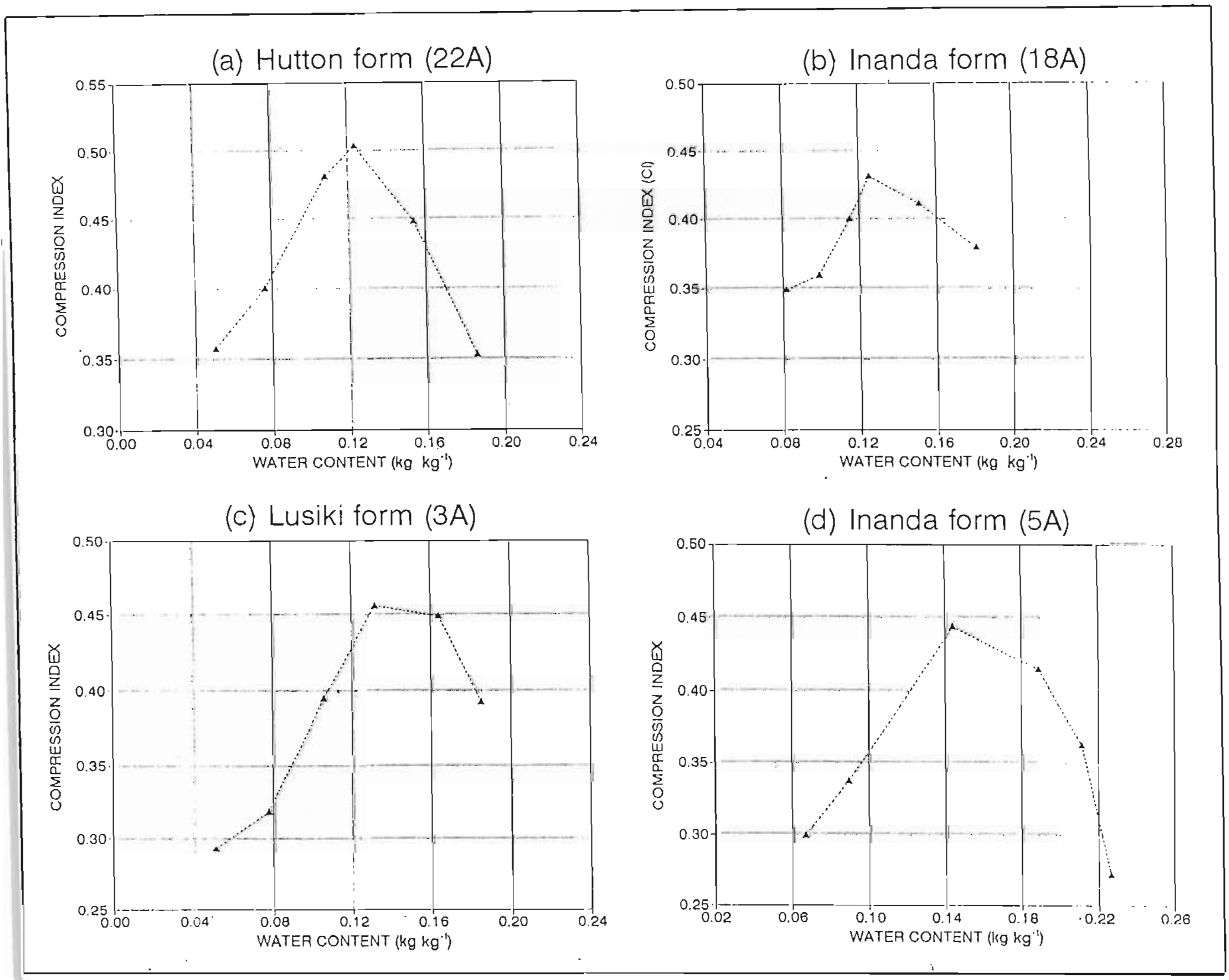
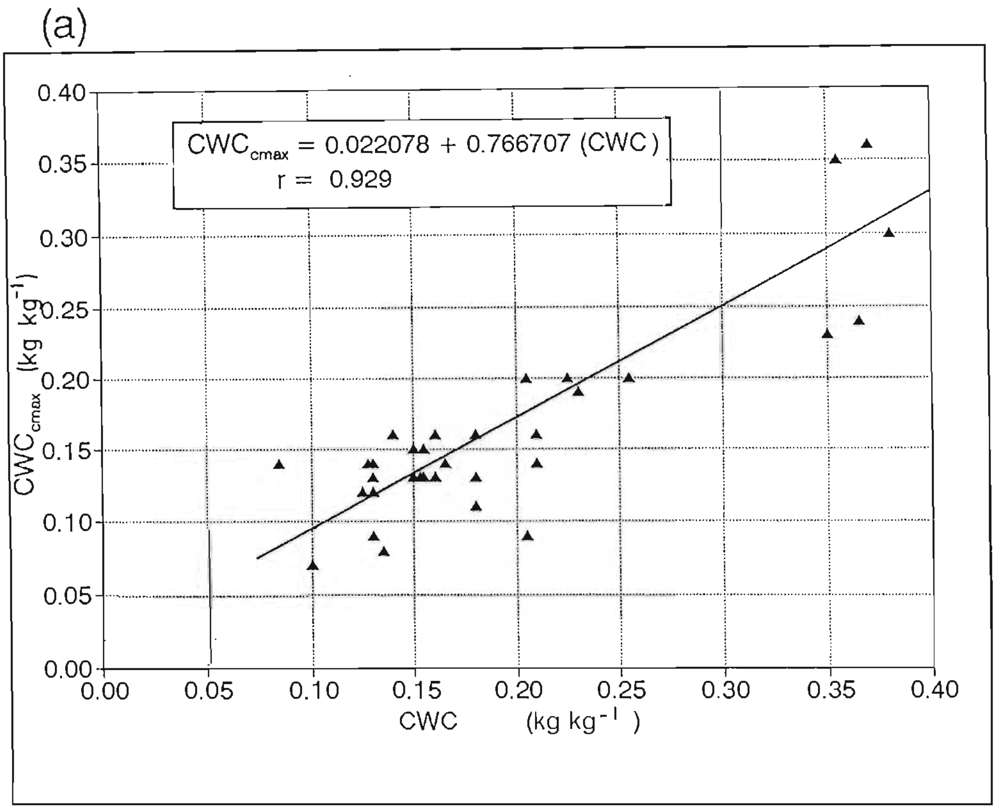


Figure 3.6: The relationship between compression index, *C*, and water content for four forestry soils.



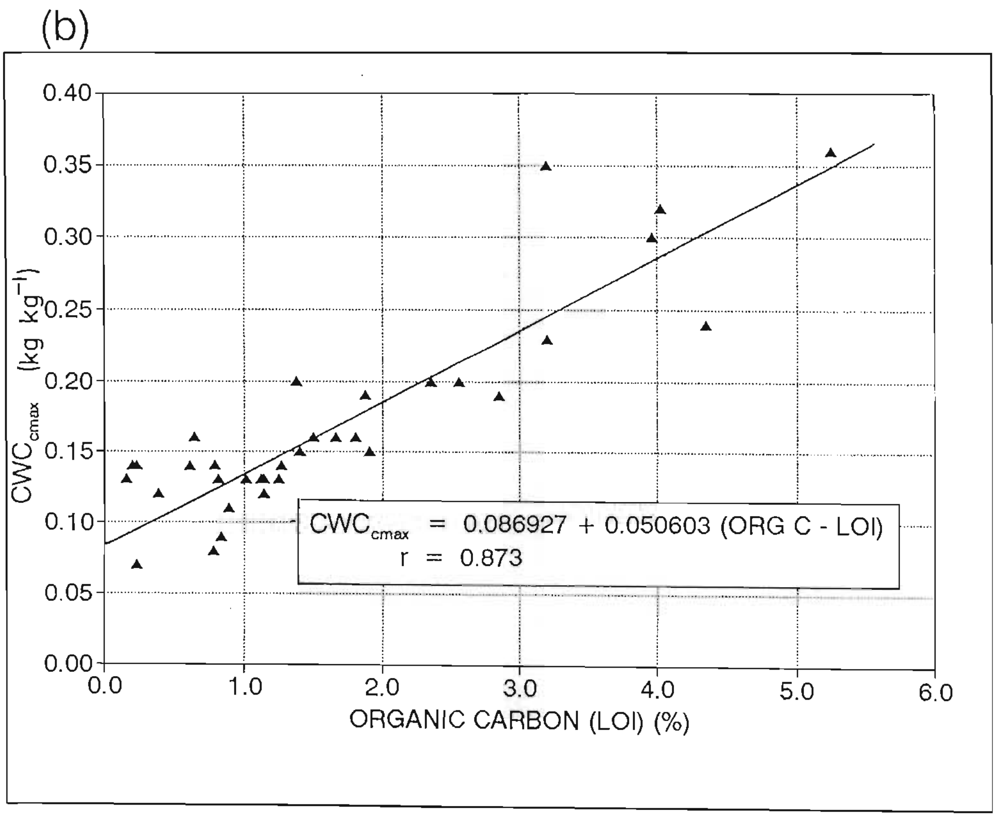


Figure 3.7: Relationship between CWC_{cmax} and (a) CWC and (b) organic carbon (LOI) content.

3.3.9 Assessing compaction risk in terms of both compactability and compressibility of forestry soils

From a practical point of view it is clear from this work that it is difficult to define compaction susceptibility solely in terms of either compressibility or compactibility. A better approach would be to define an index of compaction sensitivity using both measures. For example, soils which are the most susceptible would be those which have a combination of a high compression index and high compactibility. A classification for compaction susceptibility is presented in Figure 3.8 and is based on the strong correlations between clay plus silt and C_{max} on the one hand and between organic carbon (LOI) and MBD on the other. A knowledge of both properties will enable a rapid evaluation of the likely compaction behaviour for a given soil.

Figure 3.8 was constructed by selecting arbitrary classes for the delineation of very low to very high compactibility and compressibility classes. These are given below:

Class	**MBD (Mg m^{-3})**	C_{max}
Very high	> 1.8	> 0.5
High	1.6 - 1.8	0.4 - 0.5
Moderate	1.4 - 1.6	0.3 - 0.4
Low	< 1.4	0.2 - 0.3
Very low	-	< 0.2

The organic carbon (LOI) and clay plus silt contents which corresponded to these limits were determined from Figures 3.2g and 3.4c respectively. Ratings were assigned to each susceptibility class, increasing from 1 to 5 going from very low to very high for both compactibility and compressibility. These ratings were added together for both susceptibility classes to obtain a joint rating. Contours were constructed corresponding to areas which had similar ratings. Thus, soils with high compressibility and moderate compactibility (4 + 3 = 7) had a similar rating to a soil with low compressibility and very high compactibility (2 + 5 = 7).

It is worthwhile noting that, in very few circumstances, soils which are highly compactible are also highly compressible. In general as the clay plus silt fraction increases the compressibility increases and compactibility decreases. In the absence of organic carbon (LOI) data for a particular soil, compactibility (MBD) can also be evaluated from clay plus silt data by considering the limits given above in conjunction with Figure 3.2b.

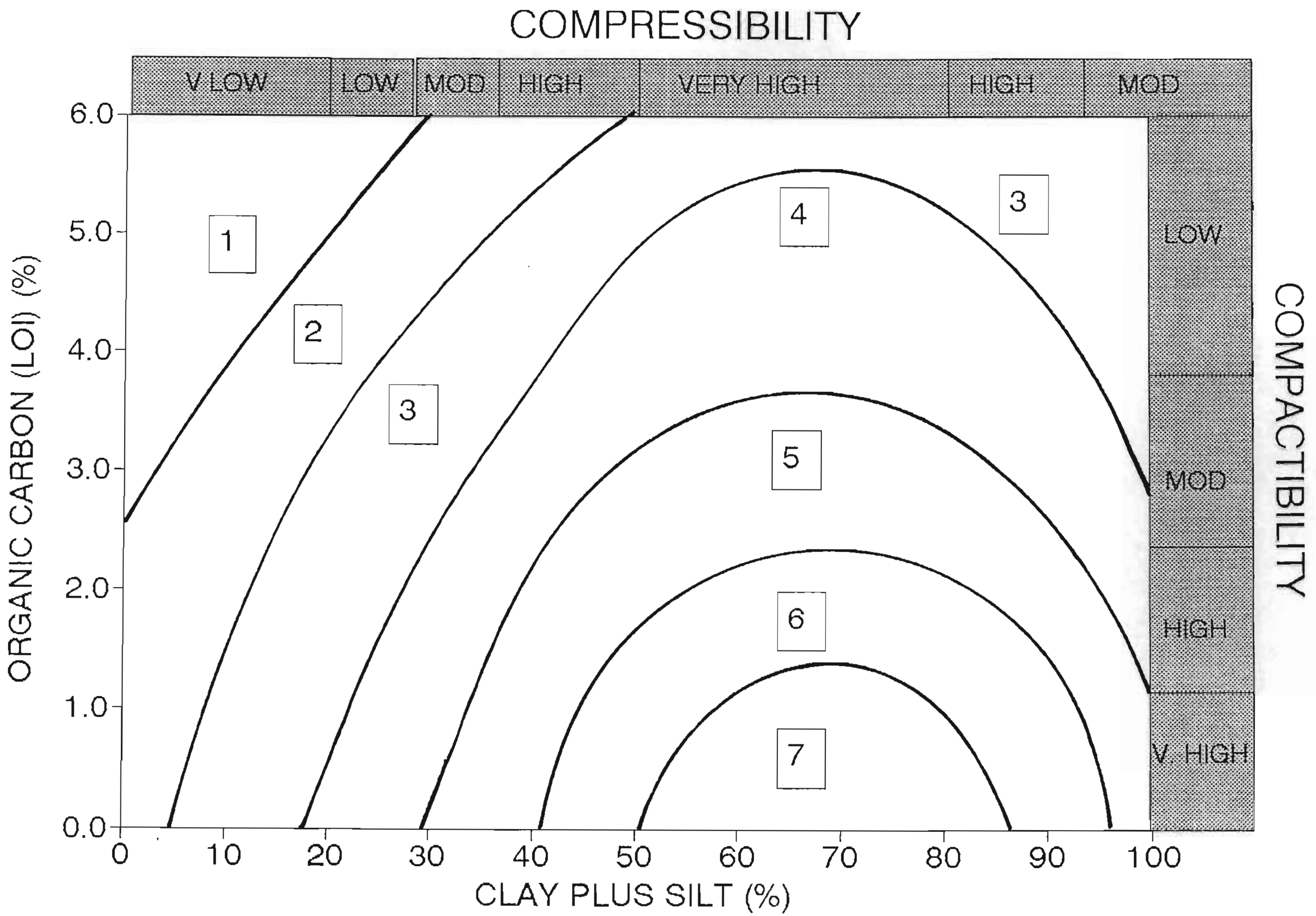


Figure 3.8: A classification for compaction risk assessment of South African forestry soils based on the relationships between organic carbon (LOI) and compactibility, and between clay plus silt content and compressibility. Compaction risk, as a combination of compressibility and compactibility, increases on moving from Areas 1 to 7.

3.4 DISCUSSION AND CONCLUSIONS

This study of a wide range of forestry soils has established that compaction susceptibility, as measured by compressibility and compactibility, can be assessed accurately by routinely measured soil properties. In particular, excellent correlations have been achieved between compactibility (MBD) and clay plus silt percentage and organic carbon content measured by loss-on-ignition (LOI). Strong relationships were recorded between compressibility (C_{max}) and clay plus silt and to a lesser extent clay content.

C_{max} and MBD were influenced more by particle size distribution than by organic carbon content. This was apparent from the very good correlations achieved between C_{max} and MBD with LOI organic carbon content and the poorer correlations with Walkley-Black (WB) organic carbon. It is likely that organic carbon measured by LOI reflects in part a textural component, probably due to the loss of structural water during ignition and its inclusion in the mass calculation. An explanation for the greater effect of particle size distribution over organic matter on compressibility could be related to the amount of organic matter not being high enough to interfere with the mineral particle interfaces sufficiently to hinder compression. The view, proposed by Mitchell (1967) and supported by the data of Larson *et al.* (1980), that soils with greater than 33% clay will behave like clays because they are essentially a clay matrix with sand particles embedded within is not supported by the data in this work. It is proposed that the widely varying compression behaviour of soils with above 33% clay is due, in part, to the very different particle size distributions and varying initial porosities of the finer textured soils. Though the effect of organic carbon would appear to diminish with increasing clay content, an interactive effect with the mineral fraction cannot be discounted.

The range of maximum bulk density (MBD) values encountered in South African forestry soils is large, ranging from 1.21 to 2.00 Mg m^{-3} and corresponding to critical water contents (CWC) from 0.08 to 0.41 kg kg^{-1}. Compared to other studies in South Africa, some extremely low MBD values were obtained and are attributed mainly to the very high clay plus silt contents and to a lesser extent high organic carbon values. A knowledge of parent material would provide a very good first approximation of the compaction behaviour of forestry soils.

Although a significant correlation was obtained between kurtosis and MBD, this study has shown that soil properties which reflect the grading of soils, other than kurtosis, were the most important in the prediction of MBD. This is in contrast to the findings of Moolman (1981) and Van Huyssteen

(1989) who noted that kurtosis was the most important size distribution parameter to include in a model to predict MBD. A possible explanation for this is that soils with a wide range of textures and organic carbon contents were used in this study. Because of this, a situation occurred where soils with very different textures, and therefore compactibility, had similar coefficients of kurtosis. For example, sands and silty clays both possessed similar high coefficients of kurtosis by virtue of the concentration of particle sizes within one or two adjacent particle size categories but had very different MBD values. In such circumstances it was deemed necessary to normalise kurtosis with respect to GMD and this had the effect of improving the correlation between MBD and kurtosis.

Critical water contents for MBD (CWC) and C_{max} (CWC_{cmax}) were significantly correlated with clay plus silt and organic carbon content. In addition, although there was a highly significant relationship between CWC and CWC_{cmax}, CWC was generally higher than CWC_{cmax}. This is indicative of the greater amount of energy exercised during uniaxial compression than the impact-type Proctor test.

C_{max} was adequately predicted for all soil orders in this study by the models of Gupta and Allmaras (1987) which utilised clay content as the independent variable. C_{mod} was generally under-predicted by the models presumably as the models were developed on moist to wet soils (> -100 kPa) whereas C_{mod} was the average of C values across a wider range of water contents in this study. Thus the Gupta model is satisfactory for predicting C_{max} but may have a more limited application for predicting compression behaviour of dry soils. This is of great importance from a practical point of view for South African forestry conditions as soils remain dry for much of the year.

The work described in this chapter has demonstrated very clearly that compaction behaviour is strongly related to particle size distribution and to a lesser extent organic carbon content. Due to the nature of the soil preparation, the role of soil structure and aggregation was not investigated. Although Van der Watt (1969) suggested that aggregation is an additional variable affecting soil compactibility, this was not considered to be a major problem in this work as forestry soils generally lack a moderate to strongly developed macrostructure. In this study field soil structure of most of the soils (see Appendix 1) was dominated by a single grain matrix in the more coarsely textured soils and by an apedal, strongly microaggregated structure in soils with higher clay contents. The dependence of the current soil classification in South Africa (Soil Classification Working Group, 1991) on morphological criteria will render the classification ineffectual for the forestry land user if more emphasis is not placed on soil physical attributes such as particle size distribution. The poorer relationships between Walkley-Black organic carbon and compaction behaviour suggest that, since interactions between organic matter and mineral particles are poorly understood, limits between humic and orthic phases are of little value to the forestry land user when establishing compaction risk. Although it is a less "exact" measure of organic carbon content, the excellent correlations achieved with the more rapid organic carbon measurement by loss-on-ignition (Donkin, 1991) and compaction behaviour suggest that LOI organic carbon should be considered as an alternative to Walkley-Black organic carbon when considering compaction evaluation.

CHAPTER 4

EXCESSIVE COMPACTION OF FORESTRY SOILS: THE EFFECT OF SOIL COMPACTION ON MECHANICAL RESISTANCE

4.1 INTRODUCTION

Measurements of soil strength to estimate mechanical resistance experienced by root systems have been widely used in commercial timber plantations to characterise the compacted state of forestry soils (Sands *et al.,* 1979; Jakobsen and Graecen, 1985; Grey and Jacobs, 1987). High levels of soil strength may have a considerable influence on tree root development. Reductions in rooting depth for various tree species grown in compacted soils have been attributed to increases in mechanical resistance (Sands and Bowen, 1978; Zisa *et al.,* 1980; Tuttle *et al.,* 1988). As soil strength increases, root elongation rate decreases exponentially and eventually ceases (Taylor and Ratliff, 1969; Graecen and Sands, 1980). For trees the so-called "critical penetration resistance", i.e. when root penetration effectively ceases, is between 800 and 5000 kPa depending on species, soil type and penetrometer characteristics (Graecen *et al.,* 1969).

Soil strength is usually expressed as a parameter of resistance which must be overcome to cause physical deformation of the body of soil (Chancellor, 1971). Such parameters include shear strength, unconfined compressive strength, tensile strength and modulus of rupture. These properties are frequently used to describe the structural condition of soils (Dexter, 1988), to assist the prediction of aggregate break up during tillage (Hadas and Wolf, 1984) and to assess the potential for hardsetting or crusting of soils (Ley *et al.,* 1993). These parameters are, however, of limited value when a detailed evaluation of the soil as a medium for root growth is considered. A commonly accepted technique is to predict mechanical impedance with a penetrometer. Although the measurement of mechanical impedance in this way differs from that experienced by a root (Barley and Graecen, 1967), penetrometers have been used widely as comparative measures of soil strength and as rapid appraisals of soil compaction in the field (Campbell and O'Sullivan, 1993). Bengough (1993) has pointed out that the best indirect method of estimating soil resistance to root growth is by measuring soil resistance to a probe or penetrometer. Penetrometer resistance may also be used estimate compressibility. Farrel and Graecen (1966) and Graecen *et al.* (1969)

calculated normal stress on the basal surface of a probe, which is a component of penetrometer soil strength (PSS), and found that it was related to the compression index, angle of internal friction and apparent cohesion.

A factor limiting the use and interpretation of penetrometers in the field or as an index of excessive compaction is that there is usually an insufficient data base for penetrometer resistance as a function of soil water content and bulk density (Gupta and Allmaras, 1987; Bennie and Burger, 1988; Van Huyssteen, 1989). A widely accepted norm has been to measure penetrometer resistance at field capacity, which is essentially a reference point. Such a standard, however, has many drawbacks. For example, it is practically impossible to infer strength characteristics throughout the whole available water range from a single measurement. It is likely that the success of the penetrometer in agricultural soils has been related primarily to the penetrometers' ability to **qualitatively** detect abrupt changes in soil strength, such as depth to a plough pan. On the other hand, Bennie (1991) has pointed out that it is practically impossible to measure the mechanical impedance experienced by a growing root.

As soil strength is strongly related to water content (Graecen, 1960) it may vary considerably throughout the year with wetting and drying cycles. Spain *et al.* (1990) reported large seasonal fluctuations in penetration resistance in three tropical forestry soils, the magnitude of these changes depending upon parent material. The dependence of the relationship between soil strength and water content is strongly influenced by the degree of compaction (Mirreh and Ketcheson, 1972) and this may affect forestry management practices such as the timeliness of tillage and site preparation practices. Gerard *et al.* (1982) have pointed out that the need for high energy demanding deep tillage of soils - a common practice in the establishment of new forestry plantations - could be predicted more accurately with an improved understanding of the factors influencing mechanical impedance of soils. Moreover, ripping, ploughing or pitting of compacted soils when dry may result in an undesirable cloddy tilth. Planting of seedlings in such situations is difficult and time consuming and widespread seedling mortality under these conditions has been recorded (Moehring and Rawls, 1970; Smith and Van Huyssteen, 1992).

The importance of soil strength in water relations studies is generally overlooked. Because soil strength usually decreases as soils become wetter, it is not immediately obvious whether better root growth in wet soil is due to lower soil strength, better soil water status, or a combination of both (Graecen and Sands, 1980). Sands and Bowen (1978) showed that significant reduction in the root growth of *P. radiata* occurred in compacted soils before aeration became a problem and attributed this to high soil strength. Similarly, a number of authors have shown that root penetration is controlled solely by soil strength and is independent of water potential (Taylor and Gardner, 1963; Greacen and Oh, 1972; Taylor and Ratliff, 1969). This is important in South African forestry soils which remain dry for much of the year. As a soil dries, the movement of water through the profile towards the roots is too slow to be an important factor in supplying the requirements of rapidly transpiring plants such as trees. Therefore tree roots must continuously permeate the soil and areas of favourable soil strength in order to utilise the stored water most effectively (Nambiar and Sands, 1992).

In natural soils cohesion forces hold particles together and frictional forces prevent particles sliding against each other. Both these processes cause the soil to resist deformation (Yong and Warkentin, 1966). Water content plays a major role in soil strength development as it directly affects soil cohesion by influencing the strength of interparticle water bonds. In non-cohesive soils, however, a large proportion of resistance is due to particle roughness and shape (Cruse *et al.,* 1980). Pore size distribution influences soil strength by its effect on water content and therefore matric potential which controls effective stress (Towner and Childs, 1972; Vepraskas, 1984). The effective stress for unsaturated materials is equal to the pressures with which soil particles are pulled together by water molecules. Thus Vepraskas (1984) reported significant relationships between cone index and effective stress and showed how this relationship changed depending upon the level of compaction. In this way soil compaction and soil texture which control pore size distribution (Gupta *et al.,* 1989) may affect the important relationship between soil strength and water content.

While it is clear that mechanical resistance is related to water content and bulk density (Taylor and Gardner, 1963; Barley and Graecen, 1967; Bennie and Burger, 1988), the literature is conflicting on the role of soil physical and chemical properties on the development of soil strength. Soil strength has been shown to be influenced by soil texture (Mathers *et al.,* 1966; Byrd and Cassel, 1980). Gerard (1965), for example, showed that the strength of remoulded briquets increased with increasing silt and clay contents. Similarly, Bennie and Burger (1988) illustrated the relationship between penetration resistance and silt plus clay content for a number of predominantly sandy textured soils (clay plus silt < 20%). Penetration resistance for the same moisture content and bulk density increased with increasing amounts of silt plus clay. Increasing amounts of clay may also be responsible for increases in soil strength and retardation of root growth (Gerard *et al.,* 1982). Utilising reconstituted soil cores containing between 66 and 83% sand, all with a similar bulk density, Byrd and Cassel (1980) reported a direct correlation between soil texture and mechanical resistance.

Some studies have been less conclusive regarding relationships between strength development and soil physical and chemical properties. Stitt *et al.* (1982) studied the relationship between physical, chemical and mineralogical properties of a group of Atlantic coastal plain soils in the U.S.A. and found no direct correlation between mechanical impedance and soil texture nor any evidence that cementing agents were affecting cone index values.

Contradictory perceptions of soil compaction in forestry plantations in South Africa underline the necessity for an understanding of the complex relationship between soil strength, bulk density, water content and soil texture and soil structure. It is often unclear whether soils which are apparently "compacted" are not simply dry. This uncertainty is exacerbated because most South African plantations occur in areas of marginal water deficit and trees dry the soil out further. In addition, overburden pressures cause soil strength increases with depth (Bradford *et al.,* 1971). Such changes, which are sometimes abrupt, commonly occur between the topsoil and subsoil and can substantially affect root development (Van Huyssteen, 1989). As water content changes throughout the year, so too does the soil strength (Spain *et al.,* 1990). Trees are perennial crops and have considerable opportunity during their lifespan to exploit areas of lower soil strength. Identification of factors affecting strength development will provide a sounder basis for evaluating the effects of compaction on soil properties and tree growth, soil trafficability and timing of tillage operations.

The aim of this part of the study was to characterise the effect of soil compaction (as reflected by bulk density) on the relationship between penetrometer soil strength and water content for a range of forestry soils, and to examine whether these relationships could be related to commonly measured soil properties.

4.1.1 Soil penetrability

The subject of penetrability in natural soils has received considerable attention in the literature. For a general review and comprehensive treatment of the subject in general the reader is directed to the more important papers on the subject. The various penetrometers, their uses and limitations are outlined by Bradford (1986). More recently, Campbell and O'Sullivan (1993) outlined the general theory of penetrometers and their applicability to tillage, compaction and trafficability studies. In the same monograph Bengough, (1993) discussed the use of penetrometers, particularly small probes, in relation to mechanical resistance and root growth.

4.2 MATERIALS AND METHODS

4.2.1 Soils and sample preparation

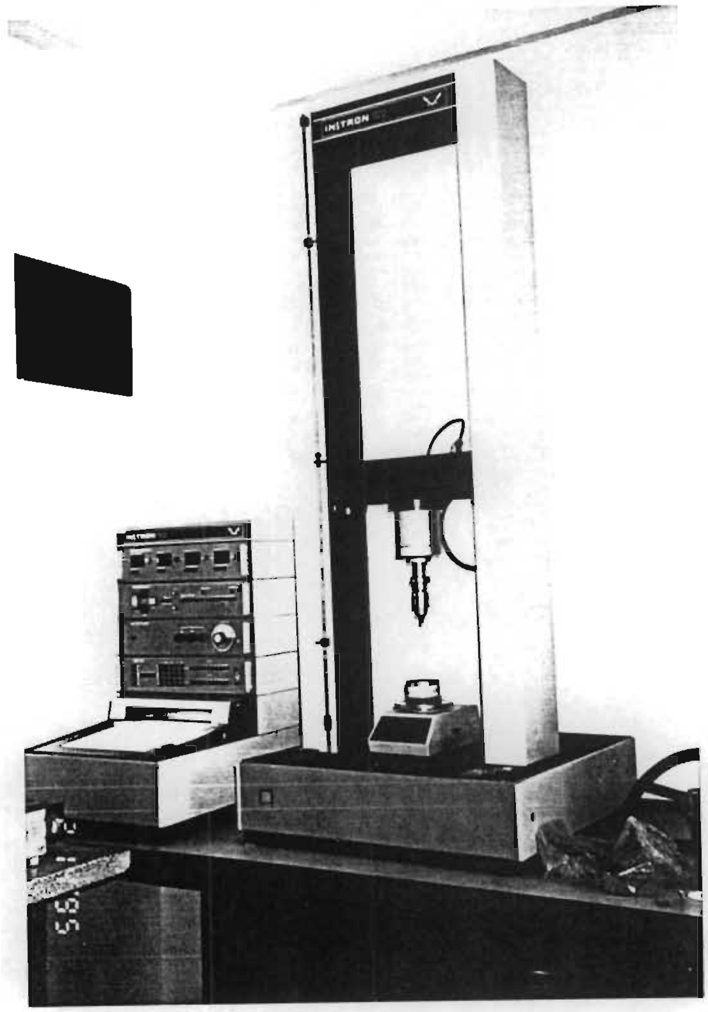
The samples used in this study were derived from two sources:

i) The "repacked" soil cores prepared for the uniaxial compression tests for all the forestry soils in Chapter 2. The soils were prepared according to the methodology outlined in section 2.2.3.

ii) Soil cores utilised during the determination of the water retention characteristics of selected forestry soils in Chapter 5. Details of the sample preparation are outlined in section 5.2.2. To avoid sample disturbance, penetrometer soil strength (PSS) was determined on all the soils at either -10 kPa or -1500 kPa after drying from saturation.

4.2.2 Penetrometer soil strength (PSS)

The compressed soil cores with an attached metal base were placed on a top pan balance which was tared to zero. PSS was then measured on the compressed cores using a 60°, 2 mm basal diameter cone penetrometer relieved to 1.5 mm behind the tip (Plate 1) in order to reduce the soil-steel friction component of cone resistance as much as possible. Also the use of a 2 mm cone in 75 mm laterally confined soil cores avoids problems due to edge effects. Core diameter may affect cone resistance if the core diameter is less than 20 times that of the probe (Bengough, 1993). The penetrometer was mounted on an Instron Universal Testing Machine (IUTM) and penetrated the cores at a rate of 10 mm per minute to a depth of 40 mm (Plate 4.1). Two replicate penetrations were carried out for each soil core. Because of a malfunction in the recording chart mechanism of the IUTM the soil cores were placed on a balance which was tared to zero. Balance readings were recorded at 5 mm depth increments, producing seven readings altogether, from which an average was calculated. The initial reading at 5 mm depth was disregarded as PSS increased with depth



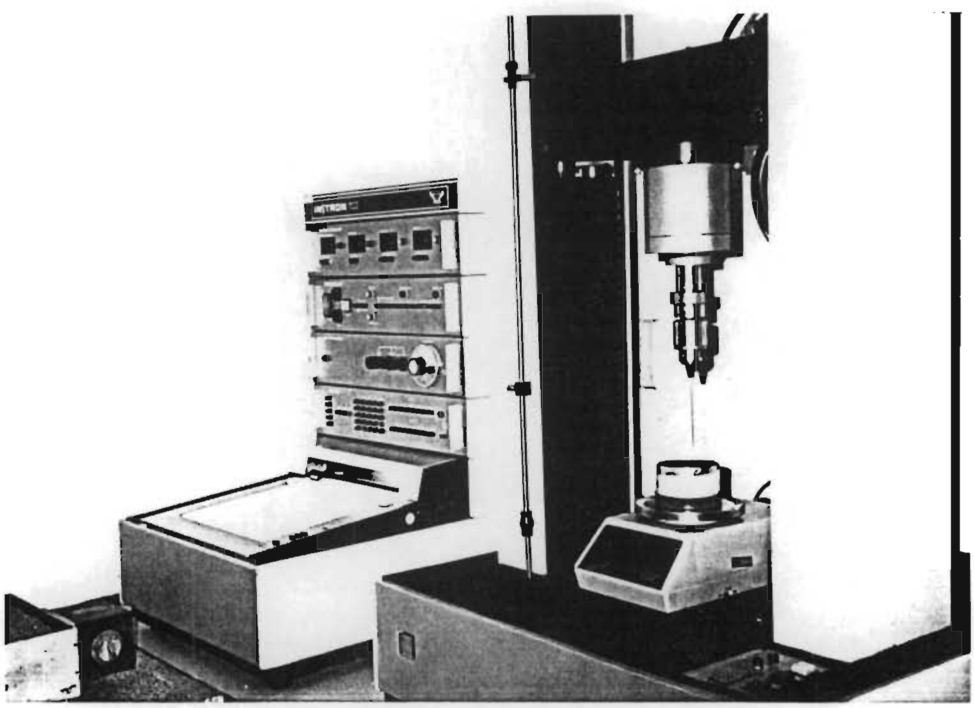


Plate 4.1: Cone penetrometer mounted on an Instron Universal Testing Machine (IUTM).

up to a certain depth. This depth, beyond which PSS became relatively constant, is known as the critical penetration depth (Bradford, 1986) which in this case was achieved for most soils between 5 and 10 mm. The force required for the penetrometer to penetrate the soil was calculated by converting the balance reading (kg) into cone resistance or penetrometer soil strength (kPa) by dividing the load (kg) by the cone basal area (m^2) (Bradford, 1986). Thus:

$$\text{Cone Resistance (kPa)} = (Mg/1000\pi r^2) \qquad [4.1]$$

where:
- g = 9.807 m/s^{-2}
- M = Balance mass (kg)
- r = Basal radius of cone (m^2)

For a cone with a basal diameter of 2 mm, a mass of 1 g recorded on the balance corresponded to a cone resistance of 3.12166 kPa. On completion of the penetration measurements the cores were oven dried and bulk density and water content were determined.

Cone resistance is made up of a pressure component required to expand the cavity for the advancing probe and a cone frictional effect related to the probe properties. Farrell and Greacen (1966) have suggested that in order to correlate root elongation to penetrometer resistance the normal point resistance can be determined using the equation:

$$P_r = P_n (1 + \tan\alpha \cot\delta) \qquad [4.2]$$

where:
- P_r = total point resistance
- P_n = normal point resistance i.e. the normal stress on the basal surface of the probe
- α = the included semi-angle of the cone
- δ = the coefficient of soil-metal friction

4.3 RESULTS AND DISCUSSION

4.3.1. Effect of soil compaction on penetrometer soil strength (PSS) versus water content relationships for various forestry soils

Penetrometer soil strength (PSS) versus water content relationships for a range of bulk densities for selected forestry soils are illustrated in Figure 4.1. These graphs have been transposed from the original data which were represented on plots of PSS against bulk density for different water contents (summarised in Appendix 6). All the graphs in this chapter have been drawn at the same scale to enable a visual comparison. Water retention data have been extracted from Chapter 5 and superimposed on the x-axis so that an initial interpretation of the PSS values with respect to available water capacity criteria can be made. As the matric potential at a given water content depends upon the compaction level (Larson and Gupta, 1980), two values of matric potential, those corresponding to wilting point (-1500 kPa) and field capacity (-10 kPa), are given in the graphs corresponding to the lowest and highest bulk densities (WPL, WPH and FCL, FCH respectively). It should be pointed out, however, that the PSS readings in this chapter were not carried out on soils dried under tension during the determination of the water retention characteristic. A comparison between PSS readings on pre-moistened soils and soils dried under tension is given later in this chapter. It should be mentioned at this stage that gravimetric water content has been used because volumetric water content or matric potential may change during penetration due to particle rearrangement whereas gravimetric water content remains constant (Koolen and Kuipers, 1983).

Some of the general features of the graphs will be discussed here. For all soils PSS increases with increasing bulk density and decreasing water content, except at lower levels of compaction when there is usually a decline in PSS as the soil becomes very dry. A feature of all the graphs is that, for a range of bulk densities, only small differences in PSS occur at water contents approaching field capacity and wetter. As the soils dry the lines diverge, illustrating that differences in soil strength for different bulk densities are greater at lower rather than high water contents.

4.3.1.1 Natal forestry soils (<20% clay) derived from Dwyka tillite, Natal group sandstone, Berea sandstone and recent sands

Figure 4.1 (a - d) shows the effect of soil compaction on the PSS - water content relationship for a range of selected Natal forestry soils with less than 20% clay. Figure 4.1a shows that only small differences in strength development were noted across a wide range of water contents for the Fernwood loamy sand (13A). A decrease in PSS occurs below a certain water content for all compaction levels except the highest (1.7 Mg m^{-3}). It has been proposed that in sandy soils, due to the lack of bridging clay plus silt, the cohesion between particles is lost as the menisci holding the sand grains together recede as the soil becomes very dry (Akram and Kemper, 1979; Panayiotopolous and Mullins, 1985). In contrast to the other soils in Figure 4.1, the Fernwood loamy sand does not undergo an abrupt change in PSS at any bulk density as water content changes. This can be primarily related to the contribution of frictional rather than cohesion forces to PSS. Surface tension forces may contribute to resistance at intermediate water contents (termed annular bridges by Panayiotopolous and Mullins (1985)) which bind soil particles together forming bonds of sufficient strength to provide a degree of resistance. These forces will be negligible when the sandy soil becomes very wet or very dry.

South African forestry soils with between 12 and 20% clay and derived from either sandstone sediments or Dwyka tillite are known to pose a number of establishment problems for forestry management due to their poor consistence. Two such soils, the Cartref loam (Figure 4.1b) and the Hutton sandy loam (Figure 4.1c), illustrate the sensitivity of PSS to water content especially at high bulk densities. Pronounced increases in PSS (from 1 to 5 MPa) for the Hutton sandy loam occurred over a range of water contents, from as little as 4% (by mass). Similar results have been reported by Mullins *et al.* (1990) for hardsetting soils. The proximity of the iso-stress lines for the Hutton sandy loam (Figure 4.1c) compared to the more widely spaced iso-stress lines for the Cartref loam (Figure 4.1b) is probably related to the slightly greater cohesion and available water capacity (which reflects a more even pore size distribution) of the Cartref loam due to its higher clay plus silt content (50% as opposed to 21% for the Hutton sandy loam). In addition, both these soils were characterised in the previous chapter by high compactibility and it has been observed in the field and the laboratory that both soils slump readily when they are wet up rapidly. As the soil approaches field capacity, uncompacted bulk densities increase as the smaller pores fill with water thus seriously reducing the effectiveness of the high tension of water bridges binding the particles together (Akram and Kemper, 1979). Consequently, particles succumb to gravitational forces and, in the case of the more sandy soils, slumping is often observed.

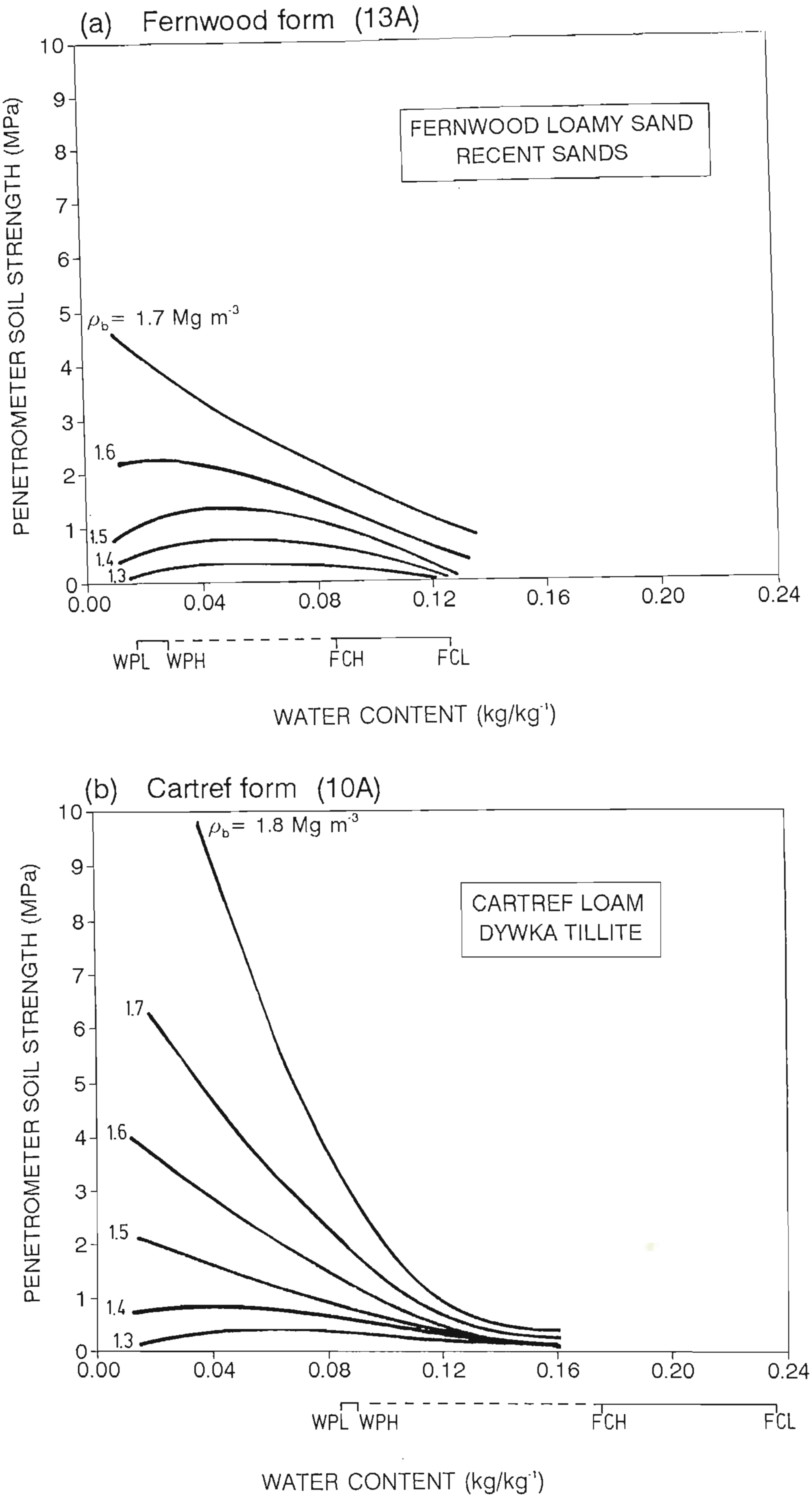
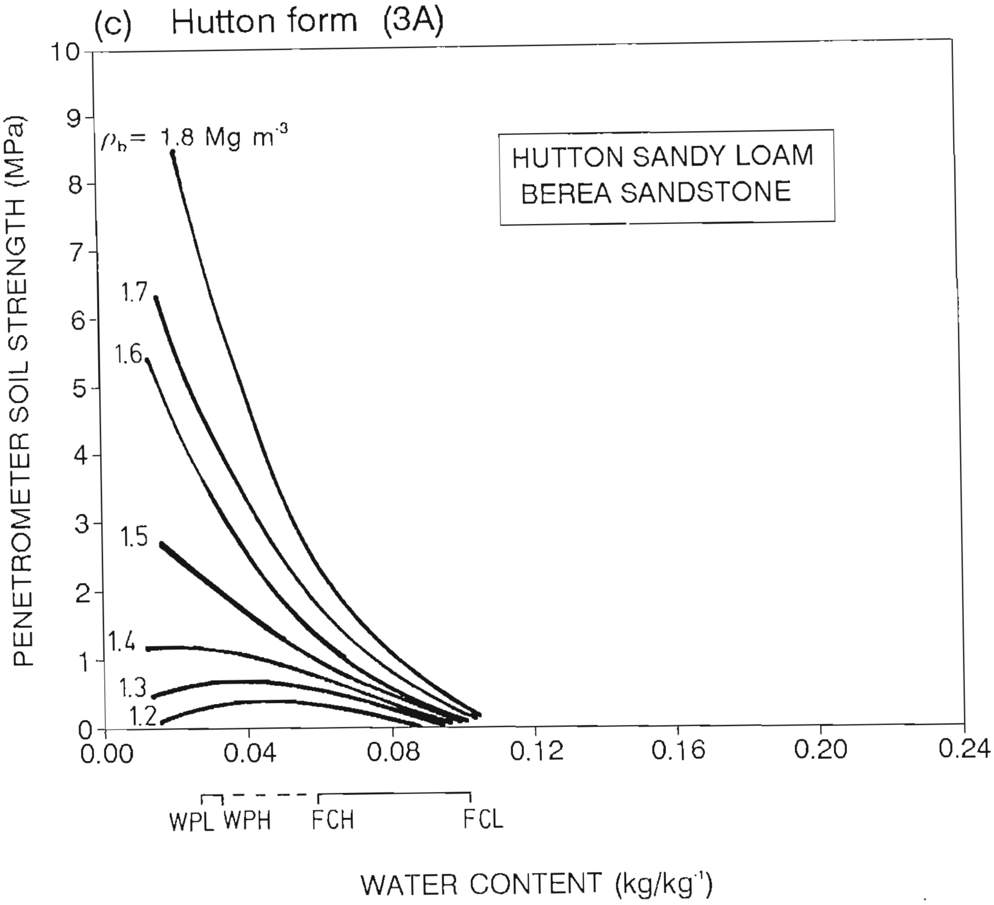


Figure 4.1: The effect of compaction on the penetrometer soil strength - water content relationship for selected forestry soils. The symbols WPL and WPH are the water contents corresponding to wilting point (-1500 kPa) at low and high levels of compaction respectively. FCL and FCH are the water contents corresponding to field capacity (-10 kPa) at low and high levels of compaction respectively.



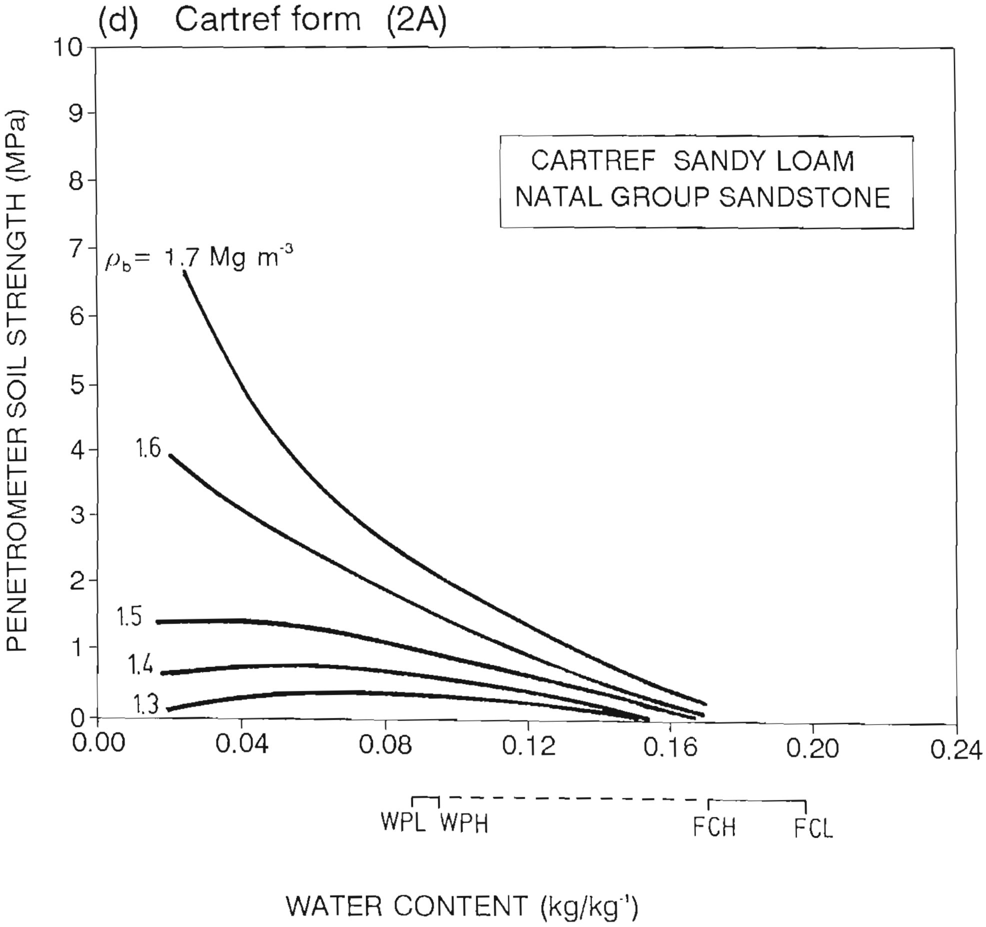
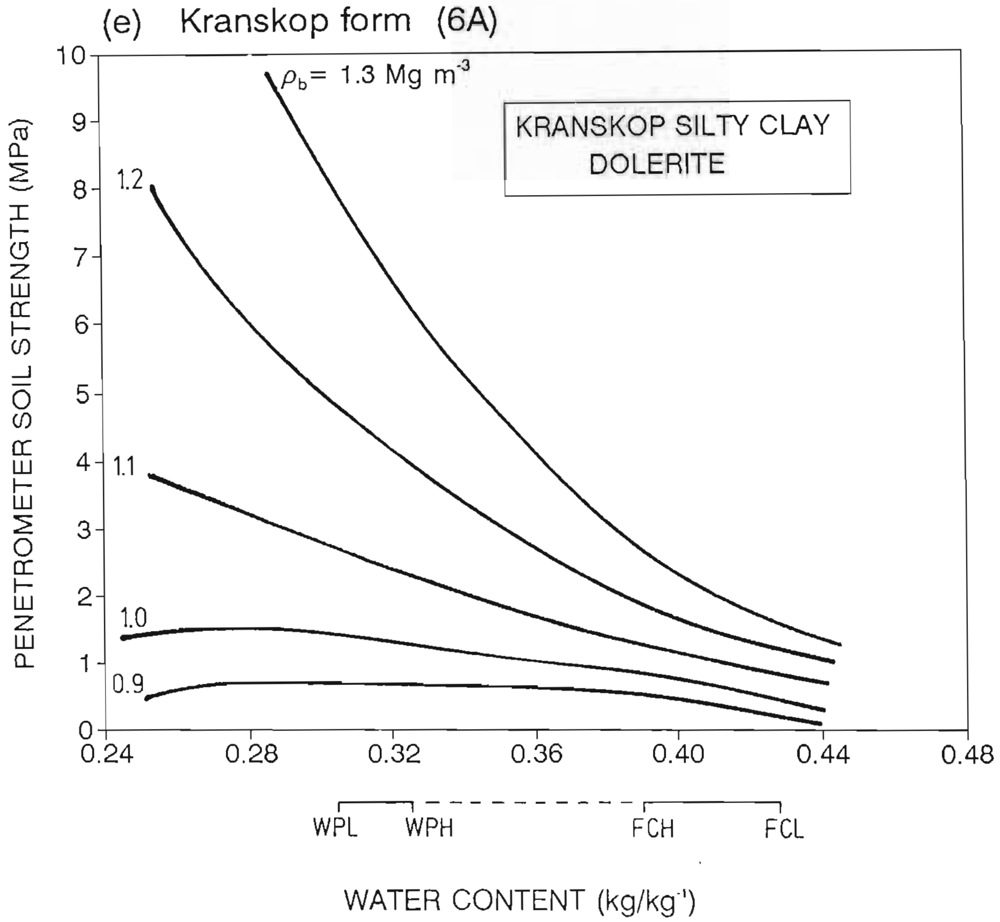
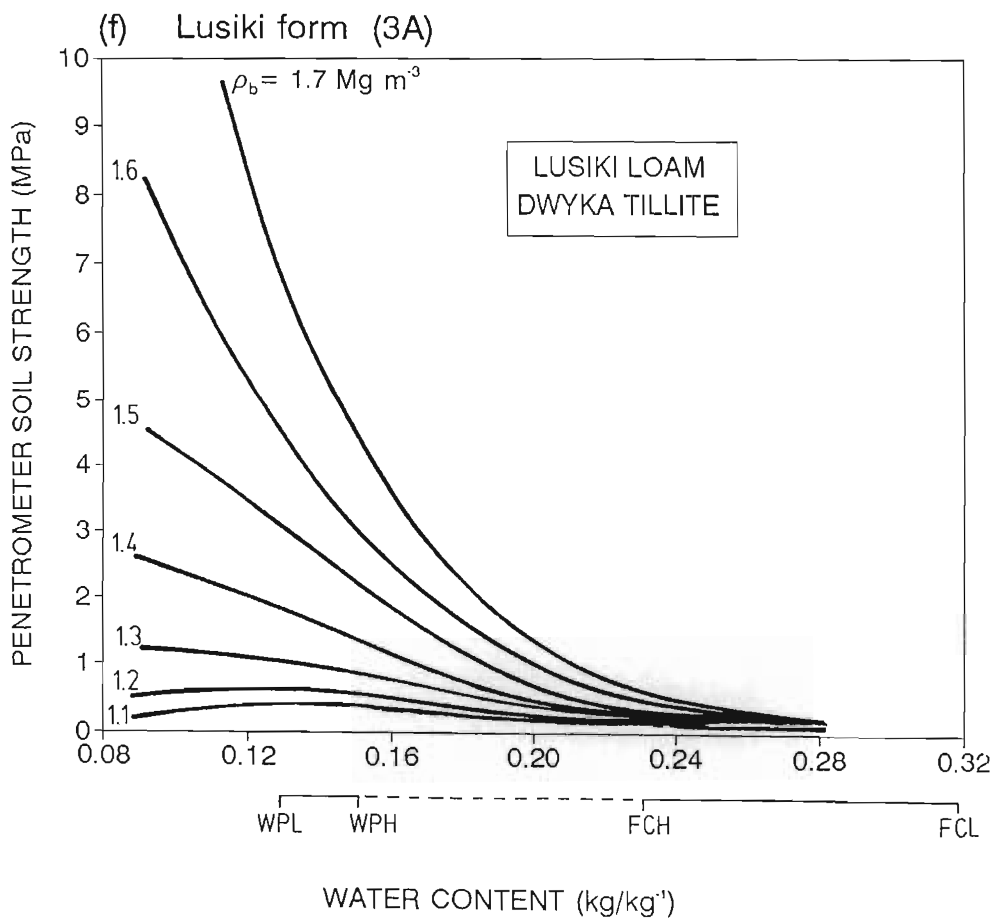


Figure 4.1: (continued)





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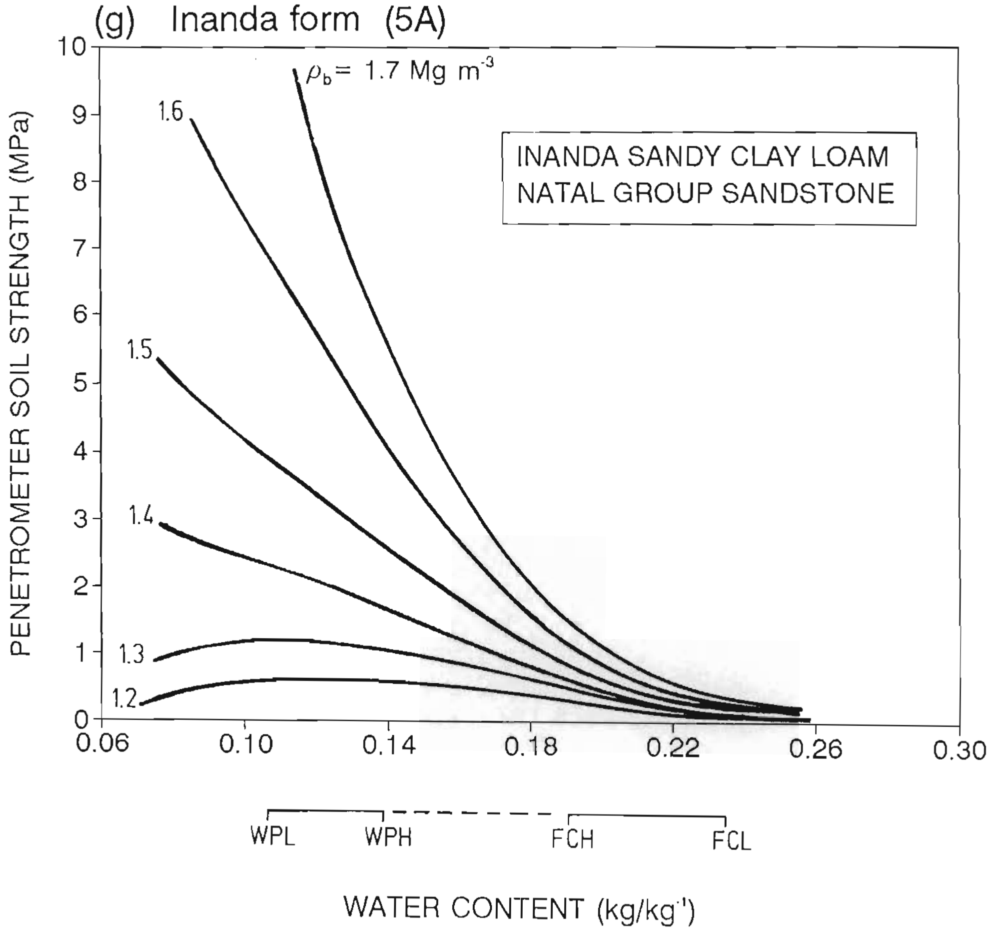


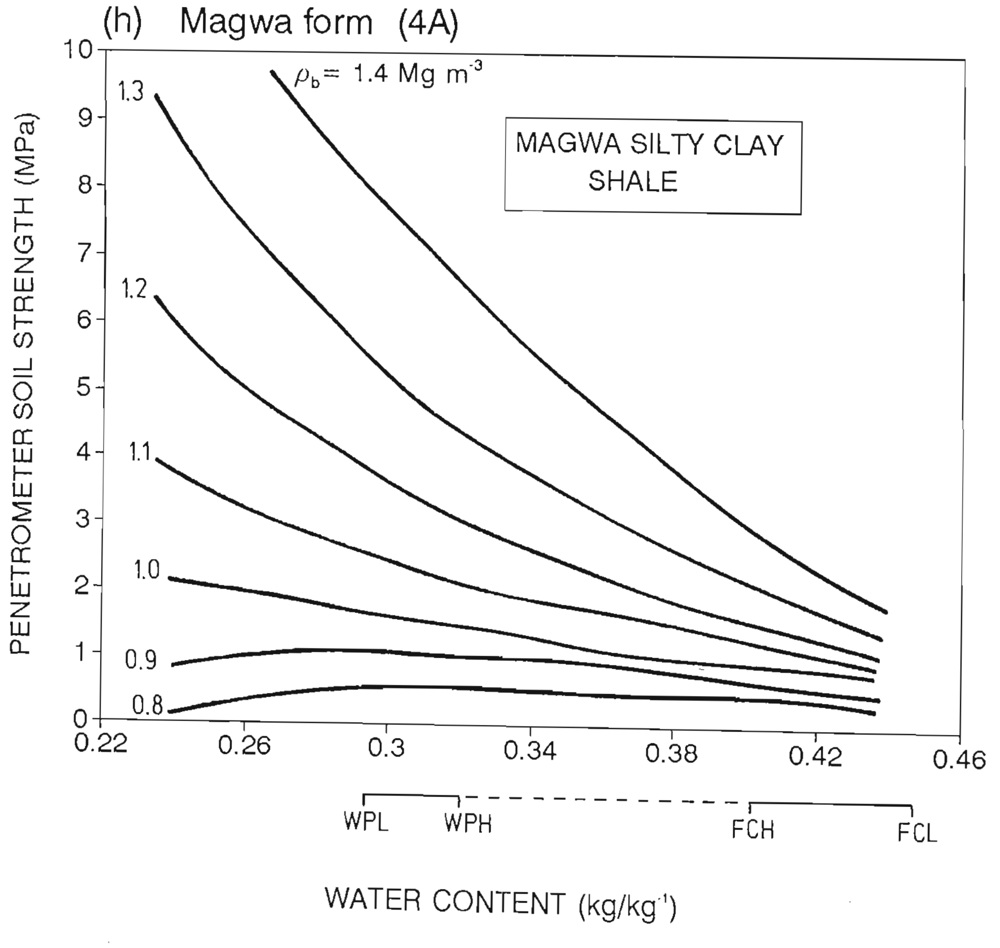
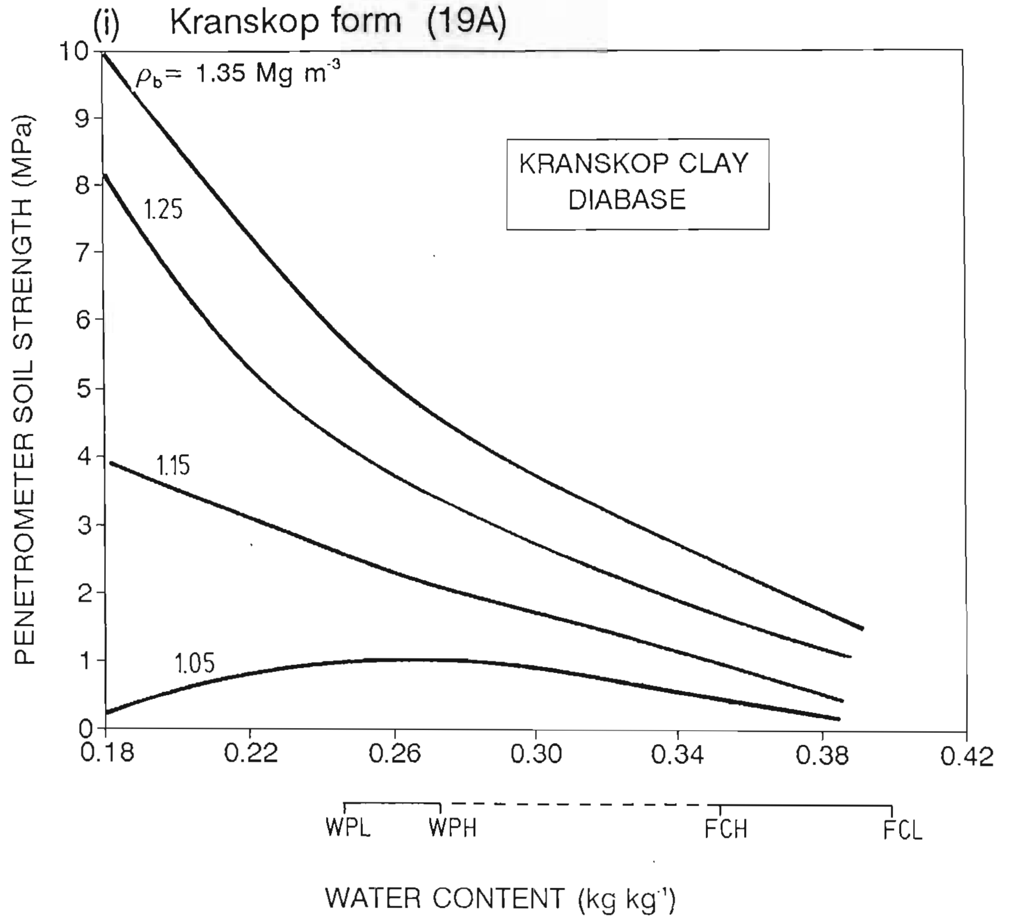


Figure 4.1: (continued)



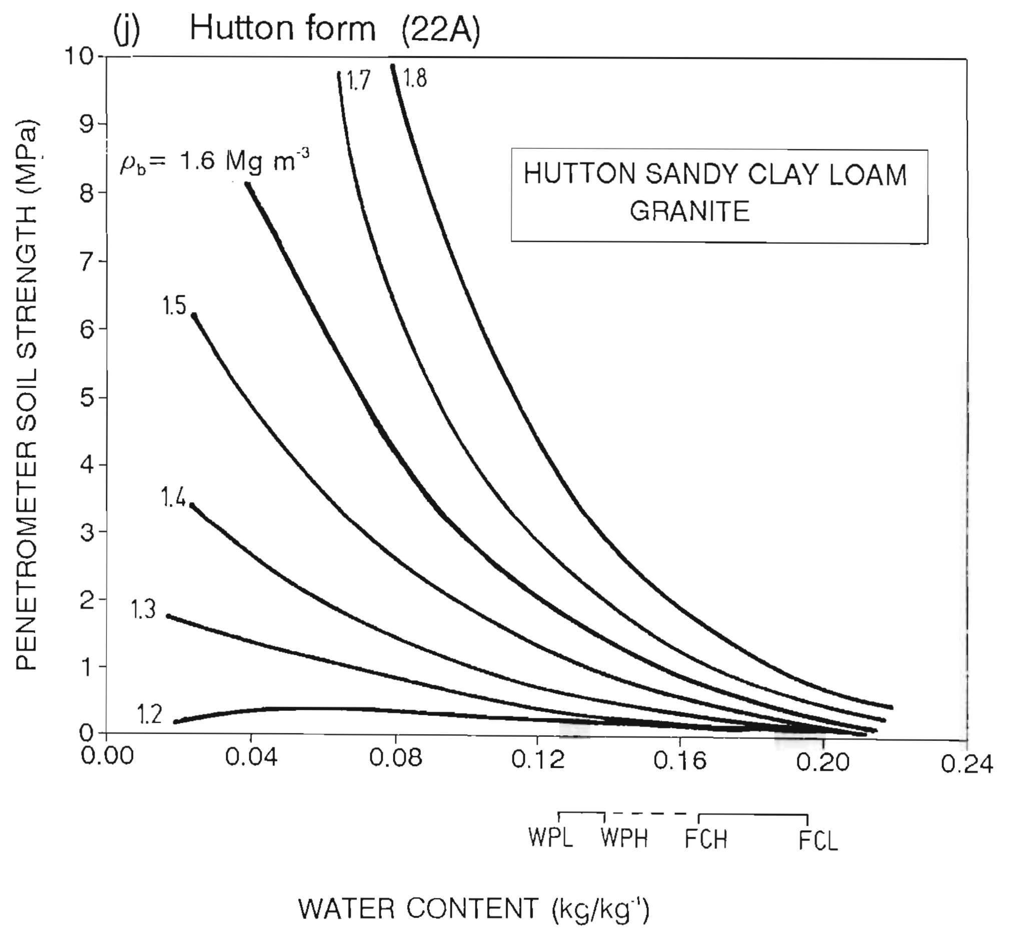
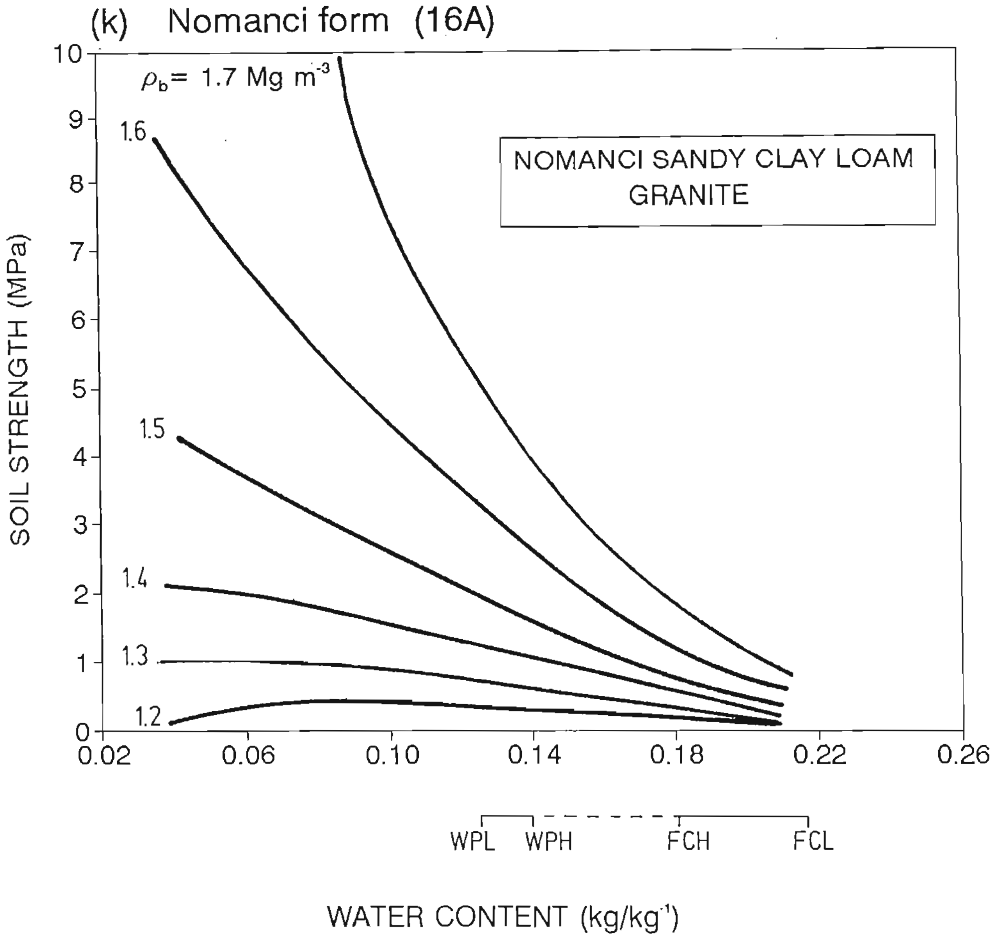


Figure 4.1: (continued)



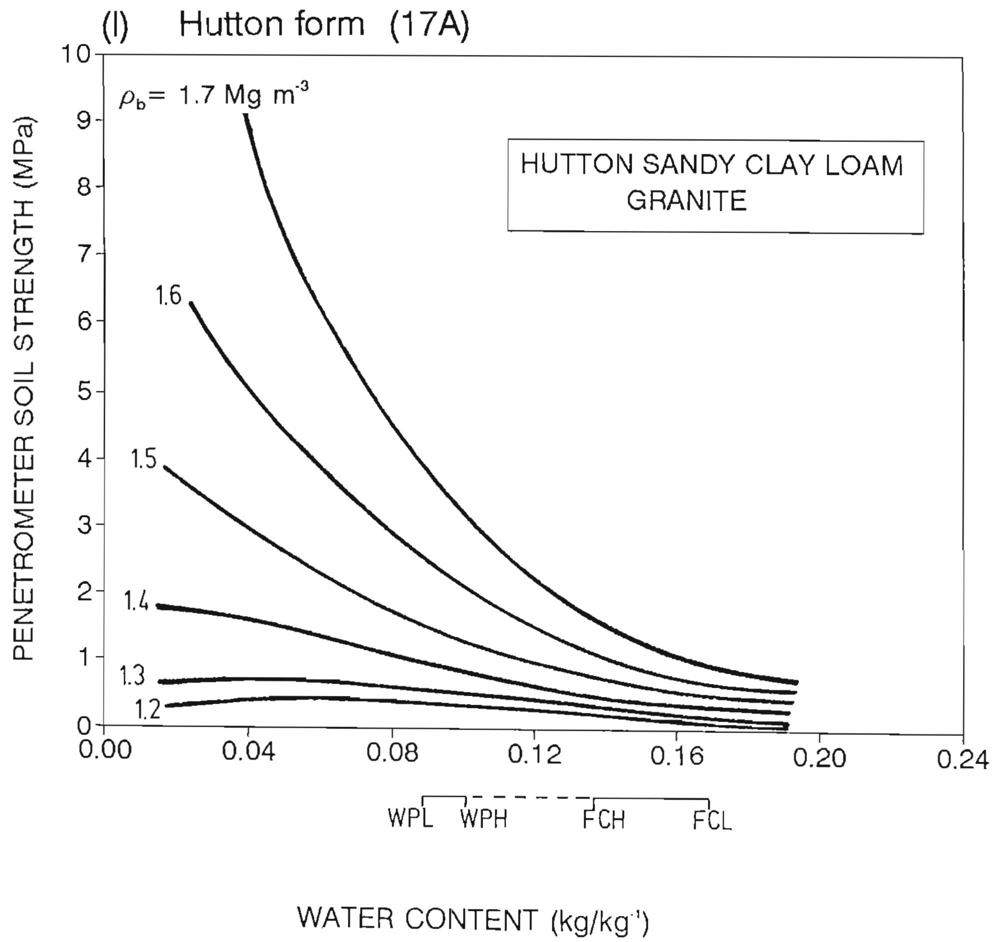


Figure 4.1: (continued)

The behaviour of the Cartref sandy loam is of interest (Figure 4.1d) as the changes in PSS with water content at all compaction levels are small despite a clay plus silt content of 30% which is intermediate between that of the Hutton sandy loam (21%) and the Cartref loam (50%). The presence of organic matter, 1.42% (Walkley-Black) in the case of the Cartref sandy loam, and nearly 4 times that of the other two soils, is believed to be the reason for this behaviour. As the soil dries organic particles disrupt the surface tension forces which contribute to soil strength (Mullins *et al.,* 1989) thus no substantial increases in PSS are noted even at higher bulk densities. Gupta *et al.* (1987) suggested that organic residue particles are more effective in separating single grain particles in sandy soils than in finer textured soils due to the lower surface area of the former. Hence Gupta *et al.* (1987) found that incorporation of residues into sandy soils had the effect of increasing the compression index rather than decreasing it. This was due to the effect of organic matter disrupting particle contacts, thus lowering frictional strength and therefore resistance to compression.

4.3.1.2 Natal forestry soils (>20% clay) derived from sandstone, tillite, shale and dolerite

Figure 4.1 (e - h) illustrates the relationship between PSS and water content at different levels of compaction for four different forestry soils from Natal with clay contents greater than 20%. A distinguishing feature of Figure 4.1 (e - h) compared to Figure 4.1 (a - d) is that changes in PSS are taking place across a wider range of water contents due to the higher clay and organic carbon contents of these soils (24% to 51% clay and 2.10 to 5.77 organic carbon (WB)). Nevertheless, similar to the soils with lower clay contents in Figure 4.1 (a - d), the PSS values still increase rapidly at higher levels of compaction as the soils approach wilting point. This effect is less pronounced for the Kranskop silty clay and the Magwa silty clay which display a more gradual increase in PSS across a wide range of water contents even for higher compaction levels (Figure 4.1e and h, respectively). These two soils also differ from the Lusiki loam (24% clay) and the Inanda sandy clay loam (30% clay) in that PSS at field capacity is higher at all levels of compaction (Figure 4.1f and g, respectively).

A comparison of the relationship between PSS and a range of bulk densities and water contents between the Inanda sandy clay loam (Figure 4.1g), the Lusiki loam (Figure 4.1f) and the Magwa silty clay (Figure 4.1h), adequately demonstrates the effect of soil texture on strength behaviour as the soils have similar organic carbon contents (2.10, 2.37 and 2.15%, respectively). The Magwa silty clay has higher PSS values than the Inanda sandy clay loam at field capacity but these values rise gradually with decreasing water content at the higher levels of compaction. The Inanda sandy clay loam and Lusiki loam, however, have very low PSS values close to field capacity the PSS changing rapidly for the higher levels of soil compaction as the soil dries.

Although organic matter strengthens wet soil and weakens dry soils (Causarano, 1993), the very high organic matter levels in this study were usually associated with higher clay contents. This is unlikely to have any mechanical effect on the more finely textured soils due to the high surface area of the clays (Gupta *et al.,* 1987). It is suggested that the dominant effect on strength properties for loamy soils and finer is soil texture rather than organic matter. As is clearly illustrated by inspection of the Kranskop silty clay (Figure 4.1e) and the Magwa silty clay (Figure 4.1h) soils derived from silica-rich parent materials, such as dolerite and shale, and which result in high clay contents, will exhibit a less extreme relationship between PSS and water content especially at high levels of compaction.

A feature of all the graphs presented here is the slight convexity of the PSS - water content relationship at low bulk densities. The PSS commonly decreases as the soil dries beyond wilting point. This slight drop in PSS as the soils become dry at relatively low bulk densities has also been recorded by Mirreh and Ketcheson (1972) and Akram and Kemper (1979). Mirreh and Ketcheson (1972) developed relationships between penetrometer resistance, bulk density and matric potential for a clay loam soil and noted that at low bulk densities mechanical resistance of the soil passed through a maximum as matric potential decreased from -100 to -800 kPa. It was suggested that the convexity of the soil resistance surface along the matric potential axis at low bulk densities, similar to the water content - PSS relationships in Figurs 4.1 (a - l), was caused by interparticle moisture bonds increasing in strength as water is drained from larger pores. Further drainage results in a larger number of broken bonds and a net decline in resistance results.

4.3.1.3 Forestry soils derived from granite and diabase in the eastern Transvaal highveld and escarpment

The results from the PSS - bulk density - water content relationships for selected forestry soils from eastern Transvaal are presented in Figure 4.1 (i - l) and reflect the results reported for Natal soils.

The PSS of soils high in clay, such as the Kranskop clay developed from diabase (Figure 4.1i), shows a gradual increase with decreasing water content and increasing compaction. The weak effect of compaction on the PSS - water content relationship is illustrated by the widely spaced iso-stress lines. PSS at field capacity is also higher than for the sandy clay loam soils developed from granite. Both Hutton sandy clay loam soils (Figure 4.1j and l) are developed from granite and the PSS of these soils displays a strong dependence on water content and compaction level. It is also indicative of the weakening influence of organic matter on the strength properties with increasing clay content that the Nomanci sandy clay loam (Figure 4.1k) possesses very similar strength behaviour to the Hutton sandy clay loam (Figure 4.1l) despite having nearly 1% more organic carbon (Table 2.2) and similar clay contents (24% and 26% respectively).

4.3.2 A quantitative description of penetrometer soil strength

The graphs presented in the previous section showed that PSS is strongly related to bulk density and water content. An appropriate multiple regression equation was sought which could explain the variation in PSS by using bulk density and mass water content as independent variables. Stepwise multiple regression (backward option) was employed (Draper and Smith, 1981) and various combinations of the variables were tested based on the nature of the relationships presented in Figure 4.1. The best equation relating penetrometer resistance to bulk density and water content for most soils is given below:

$$\log PSS = k + a \log\theta_m + b \log\rho_b + c\,\theta_m\,\rho_b \qquad [4.3]$$

The regression parameters, *k, a, b, c* and R are given in Table 4.1. For all but three of the soils studied, this relationship explained between 90% and 98% of the variation in PSS within various parameter ranges. These ranges were between 0.6 and 0.98 of relative bulk density, i.e. bulk density divided by maximum bulk density, and mass water contents ranging from 0.03 to 0.47 kg kg^{-1} depending on soil texture and organic carbon content. The results compare favourably with those of Ayers and Perumpral (1982) who related cone index of packed cylinders to bulk density and water content for four soil types and reported R^2 values of over 0.94 for each soil type. R^2 values in this study were typically above 0.90. The inclusion of log transformed variables in the final

Table 4.1: Regression coefficients for the relationship between penetrometer soil strength (PSS) and bulk density and water content (Equation 4.3) for a range of South African forestry soils. N.B. All values of R are significant at the 1% probability level.

Site No. and horizon	df	R	*k*	*a*	*b*	*c*
1A	34	0.987	2.9686	2.4746	10.1435	-8.9576
2A	39	0.979	1.5542	2.0018	10.7890	-10.5928
2E	39	0.976	3.1753	3.3924	16.0762	-25.9262
3A	39	0.959	2.3195	2.2601	9.9190	-8.3690
4A	39	0.981	3.4439	2.7773	9.7875	-6.0158
5A	65	0.974	5.3446	4.9138	14.1742	-15.4283
6A	27	0.973	5.8209	5.3663	14.7592	-9.6810
6B	33	0.959	3.3561	2.8101	11.7219	-6.0176
6B2	34	0.964	13.0281	14.1057	21.4558	21.4558
7A	27	0.986	1.0166	0.2751	8.7328	-3.5866
8A	38	0.975	8.6863	7.7916	18.155082	-20.8410
8B	37	0.949	10.7929	9.5854	18.2744	-23.7861
9A	39	0.992	13.9423	11.9259	21.1034	-34.1698
10A	39	0.976	3.2775	3.1434	12.3472	-16.8262
15A	69	0.954	1.5153	2.5721	15.0672	-12.2606
16A	51	0.977	1.2261	1.5632	11.1217	-7.8142
17A	51	0.934	-0.0234	0.5983	9.5171	-6.3019
17B	39	0.945	21.4383	15.3753	27.3661	-75.1837
18A	39	0.992	4.2831	3.7178	10.8275	-12.5038
21A	31	0.988	0.8352	0.7295	7.8065	-4.0033
21B	35	0.987	3.8404	3.2087	11.9678	-12.5657
22A	54	0.964	-0.5026	0.0389	9.0903	-5.3869
22B	38	0.894	10.5091	9.9411	16.9907	-19.4851
23A	39	0.971	4.0362	3.6946	12.1320	12.1320
24A	39	0.981	8.7256	7.7051	15.5302	-22.7417
24B	39	0.943	19.5666	16.1760	24.0709	-46.2449
25A	25	0.986	6.6628	5.7999	16.3085	-17.9887

model (Equation 4.3) is similar to the model derived by Bennie and Burger (1988) even though they worked on predominantly sandy textured soils with clay plus silt contents of less than 20%. The inclusion of a cross-multiplicative term is similar to the findings of Mirreh and Ketcheson (1972) though a physical interpretation of this is not clear.

For the soils 14A, 19A, and 25A, stepwise regression yielded the following best fit models;

(14A) $$\log PSS = k + a\,\theta_m + b\log\rho_b + c\,\theta_w\rho_b \qquad [4.4]$$

(19A & 26A) $$\log PSS = k + a\,\theta_m\rho_b + b\log\rho_b + c\,\rho_b + d\,\rho_b^2 \qquad [4.5]$$

The regression coefficients, constants and multiple correlation coefficients for these soils are presented in Table 4.2.

Table 4.2: Regression coefficients for the relationship between penetrometer soil strength (PSS) and bulk density and gravimetric water content (Equations 4.4 and 4.5) for the soils 14A, 19A and 26A. N.B. All values of R are significant at the 1% probability level.

Site No./ horizon	df	R	*k*	*a*	*b*	*c*	*d*
14A	34	0.913	-4.6291	151.669	27.0625	-104.760	
19A	37	0.941	862.261	-0.6151	1585.48	-1072.52	208.465
26A	27	0.975	-19.3212	-20.6524	16.9341	-3.5739	37.7686

4.3.2.1 Modelling penetrometer soil strength (PSS): the influence of soil physical properties

The models presented in the previous section showed that PSS could be predicted with a high degree of accuracy within a soil type for a wide range of soils utilising log transformations of bulk density and gravimetric water content. As no obvious relationships between the regression coefficients in the model and soil physical properties could be discerned, it was resolved to see whether or not this model could be extended to include soil properties which may affect the relationship between PSS and bulk density and water content. As mentioned in the introduction, previous studies have either concentrated on developing these types of relationships for one soil only (Mirreh and Ketcheson, 1972; Cassel *et al.*, 1978) or similar textures such as sandy soils (Byrd and Cassel, 1980; Bennie and Burger, 1988; Henderson *et al.,* 1988).

A step-wise multiple regression procedure (backwards option) following the recommendations of Draper and Smith (1981) was adopted to analyse the data from 29 of the 35 soils given in Chapter 2. Two soils, selected at random, were left out of the regression for model validation purposes later.

The final model selected illustrates that the relationship between PSS and level of compaction (bulk density) and water content is strongly influenced by clay content (Equation 4.6). Other textural parameters such as clay plus silt, and organic carbon (both LOI and WB) were excluded from the final model. The regression coefficients, standard errors and multiple correlation coefficient (R) are presented in Table 4.3. The final model explains almost 75% of the observed variability in PSS which is a considerable achievement considering the large number of soils in the study. The standard error of estimate was 0.2436 with a total of 1102 degrees of freedom. All the regression terms contributed significantly to the variation in PSS explained by the model (Table 4.3).

$$\log PSS = a\,\theta_m - b\,\rho_b + c\,\log\rho_b + d\,(\log CLAY) - e\,\theta_m\,\rho_b \qquad [4.6]$$

The model has confirmed the features of the relationships presented so far in that soil texture appears to have a considerable influence on the nature of the PSS - water content relationship for different compaction levels. The exclusion of organic carbon and other particle sizes including clay plus silt, from the model has shown that clay content is the particular textural component influencing the relationship rather than organic matter or other particle sizes. The results support those of McCormack and Wilding, (1981) who related penetrometer soil strength to bulk density, gravimetric water content and clay content and developed a multiple regression equation relating 2these properties to PSS which explained 78% of the variation in soil strength. Similarly, Gerard *et al.* (1982) reported soil strength, measured by a small cone penetrometer, was significantly correlated with bulk density, voids and clay content. The model presented here also supports the view of Perumpral (1983) that the variation in PSS with water content is non-linear rather than linear as suggested by Ehlers *et al.* (1983).

Table 4.3: Regression coefficients and standard errors of the terms in Equation 4.6.

Regression coefficients		Standard error	t value
a	13.133037	0.563535	23.167
b	-3.591931	0.082486	-11.893
c	21.851564	0.474617	20.4808
d	1.515273	0.044378	33.2882
e	-10.040542	0.4426	-22.6298
R = 0.894	SEE = 0.2436	MAE = 0.1780	df = 1102

The exclusion of clay plus silt from the final model was at variance with a number of authors (Gerard, 1965; Byrd and Cassel, 1980) who found a significant relationship between clay plus silt and PSS values in combination with compaction level and water content. The best multiple regression equation with clay plus silt explained 65% of the variation in PSS compared to 78% using clay content. Organic carbon, measured either by loss-on-ignition or Walkley Black, was also excluded from the final model though, as stated previously, it is likely that moderate organic carbon levels (1 - 2%) may affect the PSS of coarsely textured soils. For more finely textured soils, organic carbon levels may need to be much higher to have any effect on PSS. For example, Ohu *et al.* (1986) reported that organic matter contents of between 10 and 17% decreased the strength of three soils of varying clay content at any water content at various levels of soil compaction. Such high levels of organic matter are well in excess of the organic matter levels reported in this study.

4.3.2.2 Penetrometer soil strength (PSS) at wilting point (-1500 kPa) and field capacity (-10 kPa)

As the normal range of bulk densities and water contents varies depending upon soil texture, establishing the actual effect of clay content on PSS at a constant bulk density and water content is unlikely to be meaningful. It was decided, therefore, to compare PSS values at wilting point and field capacity for a range of selected soils at two levels of compaction; high, corresponding to a relative bulk density (RBD) of 0.9; and moderate, corresponding to a RBD of 0.8 (Figures 4.2 and 4.3). A simple linear and multiple regression was carried out for each compaction level to test the significance of the relationship between PSS and soil physical properties.

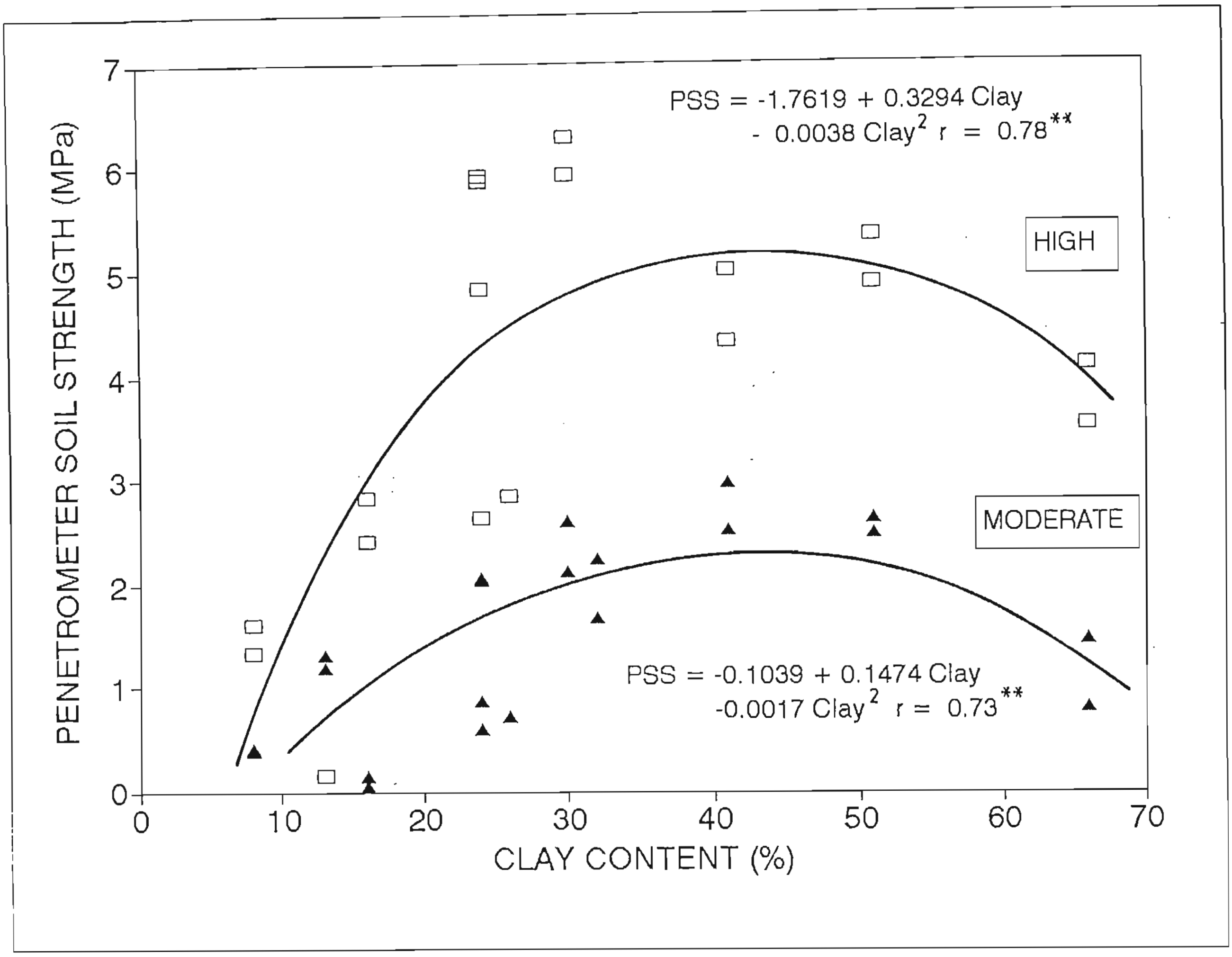


Figure 4.2: Relationship between penetrometer soil strength and clay content at a matric potential of -1500 kPa for a range of selected forestry soils at two levels of compaction corresponding to 0.8 and 0.9 of relative bulk density.

** significant at the 1% probability level

The results in Figure 4.2 show a significant relationship between PSS and clay content for both levels of compaction when soils are at a matric potential of -1500 kPa (wilting point). A power function showed a better fit of the data than a simple linear regression. This demonstrated that at both moderate and high levels of compaction, PSS at wilting point increases with increasing clay content up to a point after which PSS declines. These results tend to support the results of Ball and O'Sullivan, (1982) who showed that penetrometer resistance increased with decreasing particle size at constant water content and bulk density. Similarly, for soils with less than 20% silt plus clay, Bennie and Burger (1988) reported an increase in PSS with increasing clay content for soils at a water content of 0.1% by volume. However, as both of these studies had a limited range of soil textures, it was not clear whether PSS would continue to rise indefinitely with increasing clay content.

At field capacity (-10 kPa) a significant correlation was found between clay content and PSS for both compaction levels but the correlation was poor, being just significant at the 5% significance level. Interestingly, the correlation improved substantially when organic carbon by loss-on-ignition replaced clay as the independent variable. Figure 4.3 shows the highly significant correlation between PSS at two levels of compaction and organic carbon (LOI).

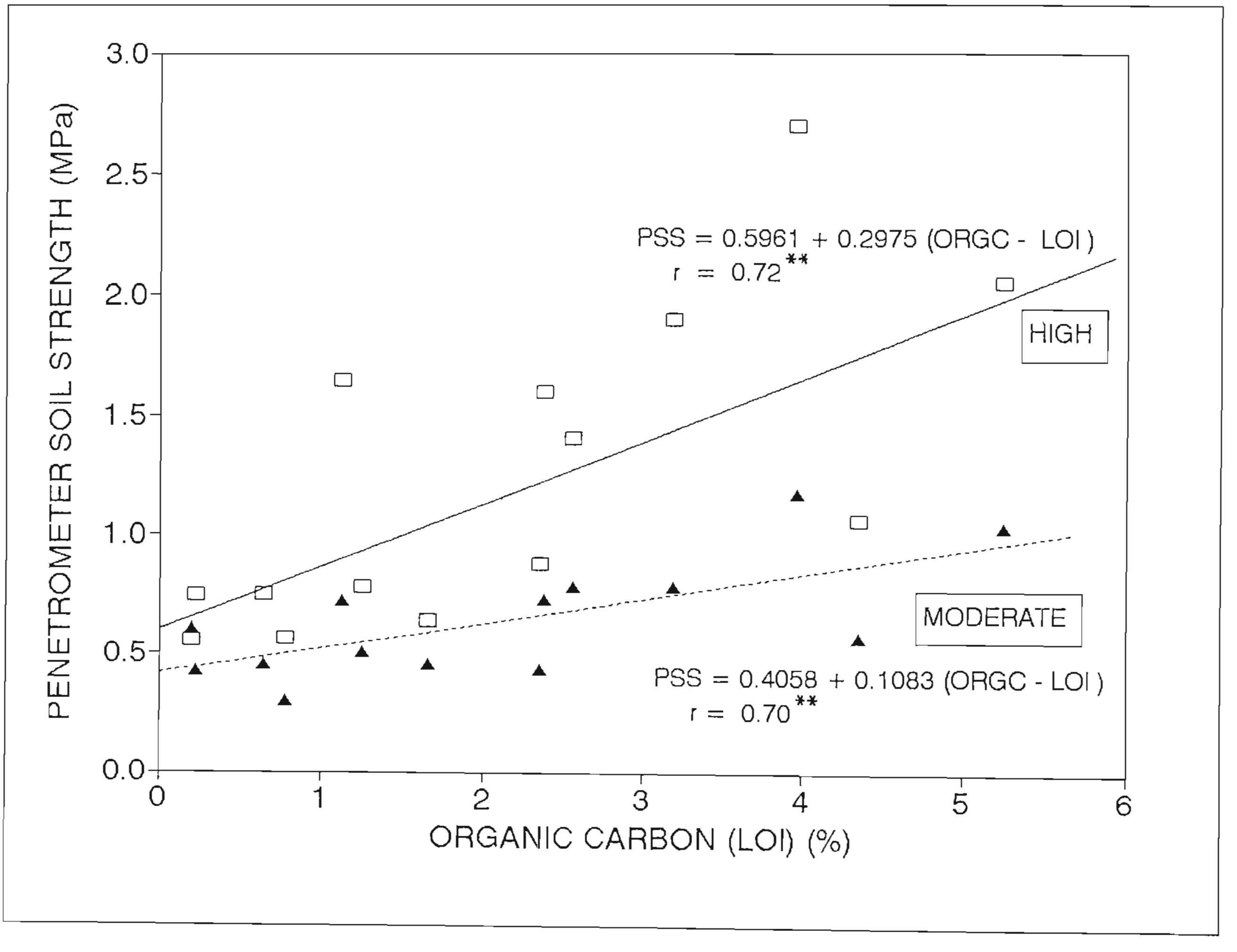


Figure 4.3: Relationship between penetrometer soil strength and organic carbon (LOI) at a matric potential of -10 kPa for a range of selected forestry soils at two levels of compaction corresponding to 0.8 and 0.9 of relative bulk density.

** significant at the 1% probability level

A significant relationship between organic carbon (LOI) and PSS at wilting point for two levels of compaction was also recorded but these correlations were not as strong as the correlations between PSS and clay content at wilting point. This suggests that organic matter plays a more important role in strength development at high water contents than at lower water contents where the effect of clay content is dominant.

The importance of clay content, rather than clay plus silt content, in affecting the PSS - water content - bulk density relationships reported previously was reinforced here. No significant relationship was noted between clay plus silt and PSS at either field capacity or wilting point for high and moderate levels of compaction.

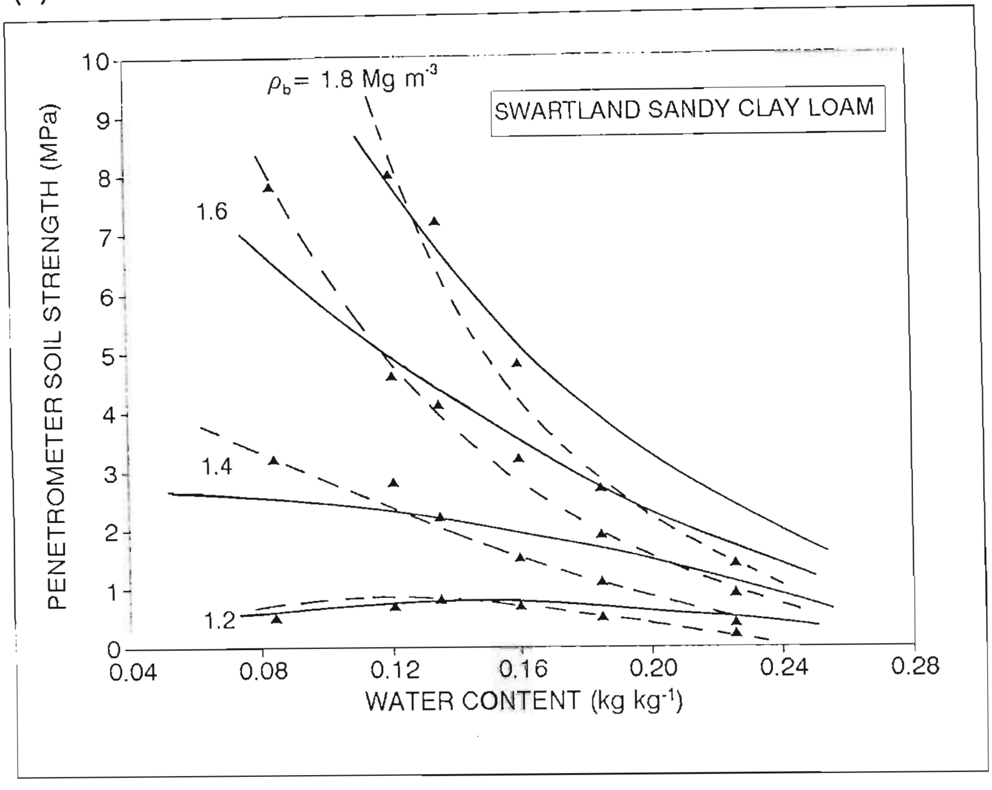
4.3.3 Model validation

The effect of compaction on the PSS - water content relationship is shown for the two soils which were left out of the original stepwise regression, a Cartref loam (10A) and a Swartland sandy clay loam (23A). This was compared to the predicted values (solid lines) using the model given in Equation 4.6 (Figure 4.4a and b). The dotted lines indicate the best fit through the data points from the individual model for each soil evaluated from Equation 4.3 and Table 4.3. In both cases the model slightly underpredicts PSS at very low water contents and overpredicts PSS at high water contents. However, considering that the model (Equation 4.6) was developed from such a large range of soils, the agreement between predicted and measured is remarkably good. This is clear evidence that clay content can be effectively utilised to predict the effect of compaction level and water content on PSS.

4.3.4 Comparison of tension dried soils with pre-wet soils

The relationships presented thus far have been established on soil samples which were wet up to the required water content and then allowed to equilibrate in plastic bags for 48 hours. It has been pointed out by Akram and Kemper (1979) that the loss of strength in disturbed dry loamy sands, sandy loams and clay loam soils would not have been so pronounced had the soils been tension dried. It was decided to compare PSS values derived from pre-wetting of dry soils with PSS of the same soils dried under tension at various bulk densities during the determination of the water retentivity curves described in Chapter 5. It was hypothesised that tension drying would result in greater PSS values than those derived from pre-wet samples. A comparison was made for eight

(a) Swartland form (23A)



(b) Cartref form (10A)

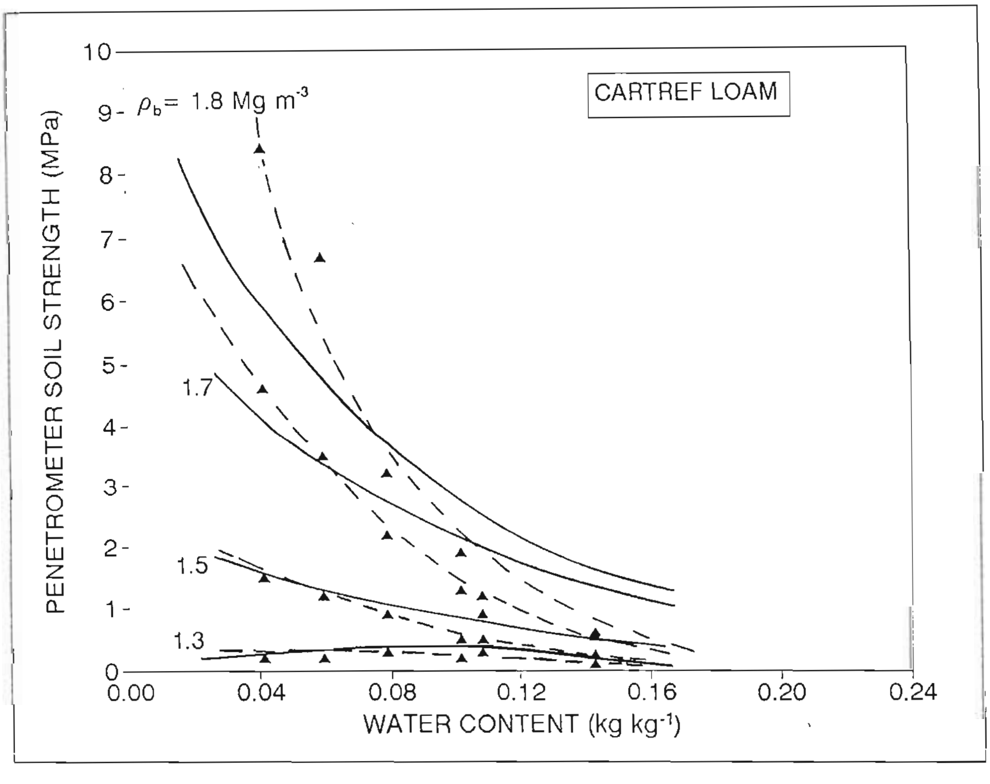


Figure 4.4: Predicted relationships (solid lines) versus measured values of the relationship between penetrometer soil strength (PSS) and water content at a range of compaction levels for (a) Swartland sandy clay loam and (b) Cartref loam. The broken lines correspond to the best fit line through the data points predicted by the models for the individual soils in Equation 4.3 and Table 4.3.

forestry soils at different bulk densities, between PSS predicted by the individual models presented in Table 4.1 and actual PSS values measured on prepared soil cores following tension drying from saturation to wilting point.

The results are presented in Figure 4.5. It is clear that the models generally underpredict PSS values by 1 MPa for predicted values less than 2 MPa. Inspection of Figure 4.5 shows that the underpredicted values are mainly for soils with low bulk densities that have not been compacted.

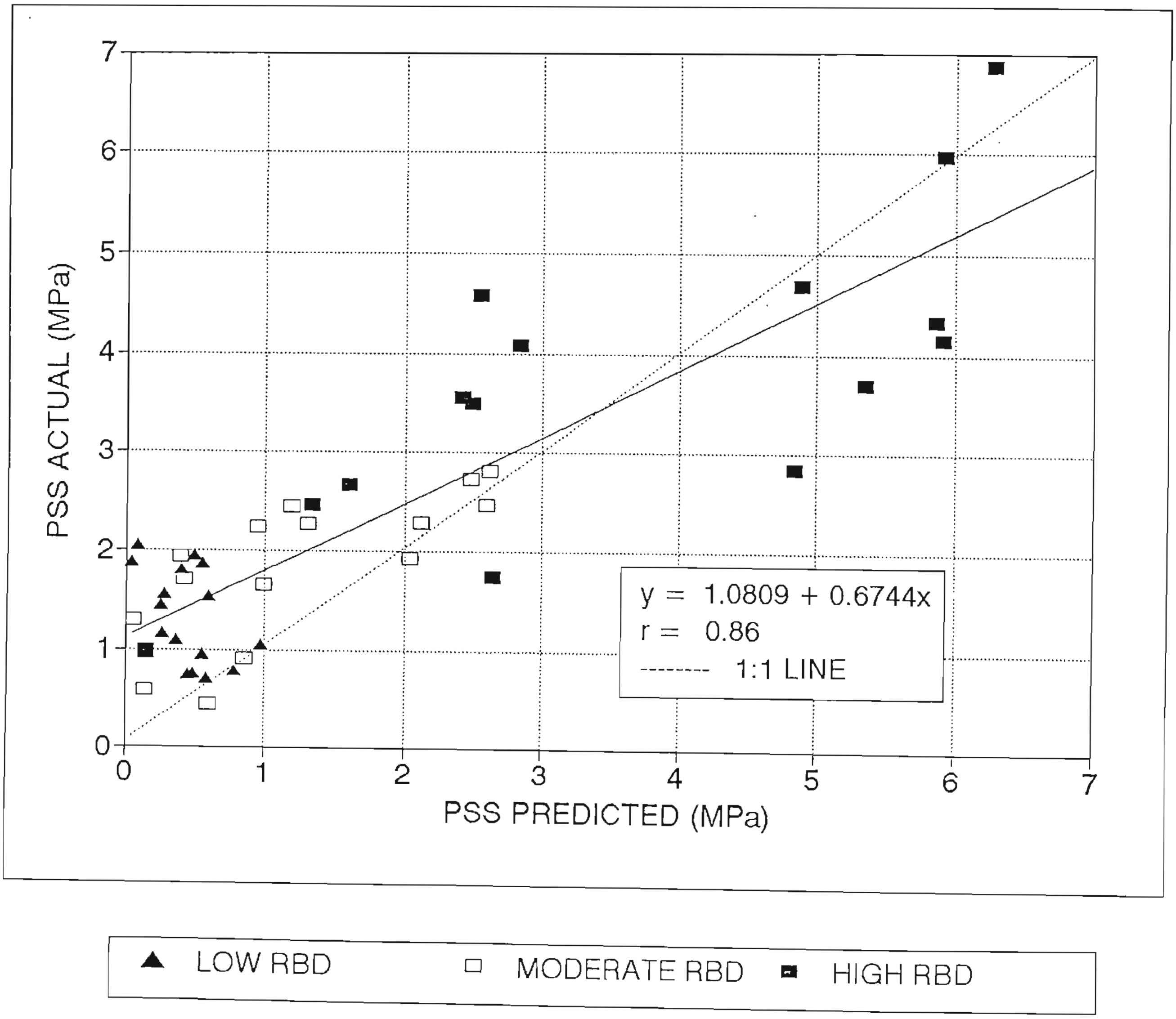


Figure 4.5: Measured values versus predicted values of PSS for a range of selected soils at three bulk densities corresponding to approximately 0.75, 0.85 and 0.95 relative bulk density (RBD) and dried to a matric potential of -1500 kPa.

This is an indication that the retreating menisci around soil particles, which may contribute to the effective stress of unsaturated soils (Mullins and Panayiotopolous, 1984; Vepraskas, 1984), are not generated as effectively by limited pre-wetting of prepared soils. However, the differences between predicted and actual values became smaller with increasing compaction (Figure 4.5). This demonstrated that, at least for moderate and high levels of compaction which were of prime interest in this study, pre-wetting of soil samples during the preparation of soils for PSS determination adequately reflects PSS values in tension dried samples.

The magnitude of the difference between actual and predicted PSS values at low compaction levels to field conditions is probably dependent upon drying rate. Gerard, (1965) showed results which suggested that a slow rate of drying was an important factor in causing more intense packing of soil particles and hence increasing soil strength.

4.3.5 Physical interpretation

Given the data presented in the previous sections, it is believed that a physical explanation for the effect of compaction, water content and clay content on soil strength is possible. Compaction increases the strength of a soil by forcing particles closer together and increasing the number of interparticle contacts, thus increasing cohesion and frictional forces considerably (Mirreh and Ketcheson, 1972; Vepraskas, 1984). There is a concurrent loss of porosity and an increase in the number of interparticle contacts. This is greater for soils with a wider range of particle sizes such as sandy loams, loams, sandy clay loam and sandy clays due to their ability to pack closely together, i.e. high compactibility (see Chapter 3). Soils within this textural range have a low available water capacity (AWC), reflecting a rapid change in pore sizes across a narrow range of water contents, which becomes even less with greater compaction (see Figure 4.1). A very rapid increase in matric potential takes place over a narrow range of water contents and the already strong interparticle bonds increase further in strength as water is drained from the larger pores to smaller pores which have smaller surface menisci (Gardner, 1961). Hence a rapid increase in PSS takes place over a narrow range of water contents, particularly at higher bulk densities. It is no coincidence that soils in this textural range are also those which are vulnerable to hardsetting (Mullins *et al.,* 1989).

The rate of PSS increase as soils dry is not as pronounced for finely and coarsely textured soils as for medium textured soils, e.g. sandy and clay soils. These differ from medium textured soils, e.g loams and sandy clay loams, due to the limited range of particle sizes (coarse or fine particles predominate) or enough cementing or bridging material such as clay plus silt in the case of sands. The gradual increase in PSS with decreasing water content as compaction increases in clayey soils is related to the more even pore size distribution after compaction since pore size distribution is not reduced by compaction to the extent found in medium textured soils. Thus, matric potential does not change as rapidly with small changes in water content and, combined with relatively low compactibility, porosity is still relatively high even at higher compaction levels. Abrupt changes in PSS are therefore not observed as the soil dries from field capacity.

A number of authors have placed great emphasis on the role of effective stress in the generation of high levels of soil strength, particularly in hardsetting soils (Mullins and Panyiotopolous, 1984; Mullins *et al*., 1989; Ley *et al.,* 1993). Mullins *et al.* (1989) emphasised that since hardsetting is usually accompanied by slumping, which itself is a process of compaction, it is difficult to separate the effects of compaction from those of effective stress in the development of high levels of soil strength. Although no **direct** evidence was presented in this chapter (effective stresses were not calculated), the nature of the relationships in Figure 4.1 (a -l) , and in particular those for the two hardsetting soils in the study, the Cartref loam (Figure 4.1b) and the Hutton sandy loam (Figure 4.1c), strongly suggest that compaction rather than effective stress, is primarily responsible for the *magnitude* of PSS. This was borne out by Vepraskas (1984) who reported a close correlation between cone index and effective stress but the contribution of effective stress to the overall soil strength was very small and depended more on factors such as bulk density and soil type. The nature of the relationships presented in Figure 4.1 show that effective stress influences the *rate* at which PSS increases but only as the soil dries at higher compaction levels for all the soils. This phenomenon is particularly noticeable for soils with low organic matter contents and clay contents of between about 12 and 40%, i.e. those categorised by Mullins *et al.* (1989) as being susceptible to hardsetting.

4.4. DISCUSSION AND CONCLUSIONS

The relationships developed in this section have provided an insight into the effect of soil compaction and water content on penetrometer soil strength (PSS), which is a measure of soil mechanical resistance, for a wide range of South African forestry soils. This study has shown that PSS is principally related to bulk density, water content and clay content for a wide range of selected forestry soils studied. Compaction level, as measured by bulk density, profoundly affects the relationship between PSS and water content. For all the soils in this study, PSS increases with increasing bulk density and decreasing water content, except at lower levels of compaction when there is usually a decline in PSS as the soil becomes very dry. Only small differences in PSS occur at water contents approaching field capacity and wetter for a range of bulk densities. Differences in PSS at various bulk densities are greatest when soils are dry rather than when they are wet.

A multiple regression equation was developed which can be used to predict the strength characteristics of a wide range of forestry soils based on a knowledge of water content, bulk density and clay content. Over 80% of the variation in PSS was explained by this model for all the forestry soils studied, provided water contents and bulk density values fall within the range of usual values for a given particle size distribution. This study has distinguished itself from others inasmuch as PSS was measured on a very wide range of very different soils for a large range of bulk densities and water contents. Furthermore, the importance of clay content, rather than clay plus silt or organic matter, was clearly shown to be the main soil property affecting the PSS - water content relationship for a wide range of compaction levels.

The model can be used to predict the likely effects of soil compaction on the mechanical impedance of soils to root penetration and, as a result, to assist in a more refined assessment of the compaction susceptibility of forestry soils. Coupled with information on critical root penetration criteria, the model could serve as an invaluable tool in soil water/fertility studies. In addition, the correlation between PSS and trafficability (Knight and Freitag, 1962) will enable a more meaningful appraisal of soil type in terrain classifications.

The inclusion of clay content as a principal predictor variable in the assessment of PSS for various levels of compaction highlights the importance of clay content in any measure of soil consistency. The effect of clay content on the relationship between PSS and water content for various levels of compaction has two important features. Firstly, for cohesive soils, increasing clay content reduces the rate at which PSS increases as the soil dries to wilting point and beyond. For non-cohesive soils in the study (approximately <20% clay plus silt), the rate of increase in PSS as the soils dry is similar to that for soils with a high clay content, despite changes taking place at very different water contents. Secondly, at wilting point, higher PSS values are obtained with increasing clay content up to about 45 to 50% clay, after which PSS declines. With increasing clay content and organic carbon (LOI) contents, PSS values are higher at field capacity, especially at higher bulk densities.

The exclusion of measures of organic matter content from the model (organic carbon by LOI or WB) indicates that organic carbon levels, though ranging from 0.16 to 5.77%, were probably not high enough for all soils to have an overiding effect on PSS. Data presented earlier in this chapter suggest that organic matter only affects PSS of soils with low clay contents, i.e. less than 25% clay. Above 25% clay, soil texture appears to be the dominant factor influencing soil strength. Soils which are discriminated into two categories, humic and orthic based on the 1.8% criteria adopted by the Soil Classification Working Group (1991), are unlikely to exhibit very different strength behaviour if they possess clay contents above 25%. For soils with less than 25% clay, an organic carbon (WB) of 1.5% is suggested as a more appropriate criterion to characterise differences in physical behaviour for soils with similar clay contents. The role of clay content in affecting PSS values for various levels of compaction again suggests, as in previous chapters, that soil texture is a principal determinant of physical behaviour in apedal, single-grain and weakly structured soils. These soils formed the basis of this study and predominate in the principal South African timber growing regions.

CHAPTER 5

EXCESSIVE COMPACTION OF FORESTRY SOILS: THE EFFECT OF COMPACTION ON THE NON-LIMITING WATER RANGE (NLWR)

5.1 INTRODUCTION

Our ability to confidently predict the likely effects of soil compaction on plant growth is hindered by the numerous interactions which occur following compaction of a soil. A further problem when predicting the effect of compaction on tree growth is that root growth of trees, unlike most agricultural crops, is generally not limited to the upper metre or less of soil. In addition, compaction is likely to have differing effects on plant growth depending upon the response of the soil to compactive effort and ensuing climatic conditions (Graecen and Sands, 1980; Boone, 1988; Voorhees, 1987).

The indices of compaction presented in the preceding chapters have given an improved insight into factors associated with compaction risk assessment of South African forestry soils. However, as Gupta and Allmaras (1987) have stated, normal measures which define the compaction susceptibility of soils do not necessarily give enough information to describe degradation of soil as a medium for plant growth. They suggested that what is needed is a comparison of air-water-soil matrix relationships at various applied loads with the limiting values for root and shoot growth. In the previous chapter the effect of compaction on penetration resistance was considered and factors which affected this relationship were identified. The focus of this chapter is to examine the extent to which compaction modifies water and air availability for a number of selected forestry soils.

As compaction may improve or worsen soil physical quality, harmful effects of compaction may be termed "excessive compaction" to distinguish them from beneficial effects (Gupta and Allmaras, 1987). Attempts to define excessive compaction have, however, proved problematic as it is almost impossible to directly correlate soil physical properties, such as texture, bulk density or soil structure, with plant growth or yield because the effect of soil physical conditions is strongly dependent on management factors (Letey, 1985). Nevertheless, studies in the past which have sought parameters of excessive compaction have usually dealt with the search for critical values of soil strength (Taylor and Gardner, 1963; Russell and Goss, 1974; Gerard *et al.,* 1982) and aeration (Voorhees *et* al., 1975; Asady and Smucker, 1989) as well as quantification of the effect of soil compaction on infiltration (Akram and Kemper, 1979) and plant available water capacity (AWC) (Archer and Smith, 1972; Reeve *et al.,* 1973; Katou *et al.,* 1987).

A particular problem faced by researchers in this type of work is the partitioning of effects. Of the four soil physical properties directly affecting root and plant growth (aeration, water, mechanical resistance and temperature), it is often difficult to hold other factors equal while varying the one of interest. Taylor (1986) pointed out that a change in soil structure is often only measured by one or two variables that may account for differences in plant growth whereas some other variable may well have caused the effect. For example, Taylor and Gardner (1963) found cotton root elongation to be reduced by increasing soil resistance as matric potential decreased in compact soils but found no reduction with decreasing matric potential where soil resistance was kept constant. Similar results were presented by Eavis (1972) and Warnaars and Eavis (1972) who showed that decreased root elongation of pea seedlings due to restricted water availability was only evident at matric potentials less than -1800 kPa. Graecen and Oh (1972) found that pea roots osmoregulate to maintain turgor over a range of soil water potentials from -280 to -800 kPa, and concluded that root penetration over this range was determined solely by soil strength and was independent of soil water potential. Similarly, Taylor and Ratliff (1969) showed that matric potential may not affect the relationship between root elongation and mechanical resistance for soils with a low water holding capacity. This was explained by similar matric potentials existing close to the the root surface due to restrictions in moisture transport.

Factors limiting root growth are obviously complex and any one of the soil physical properties listed previously may restrict root growth. In compacted soils, oxygen diffusion rate and aeration are frequently limiting for plant growth at or above field capacity (Eavis, 1972). At the other end of the scale, mechanical resistance which restricts root proliferation may occur at a water content higher than the value which would be considered limiting to plants on the basis of water availability alone (Letey, 1985). Letey (1985) has termed this range of water contents the *non-limiting water range* (NLWR) and described it as being the most convenient and effective method of characterising the soil in terms of rooting potential and depth. The concept is presented diagramatically in Figure 5.1. Topp *et al.* (1994) provided an excellent definition of the NLWR as "a soil parameter based on static measurements aimed at integrating a number of dynamic processes in order to obtain a single parameter for assessing, or providing a description of, the limitations which soil conditions inflict on plant or root growth".

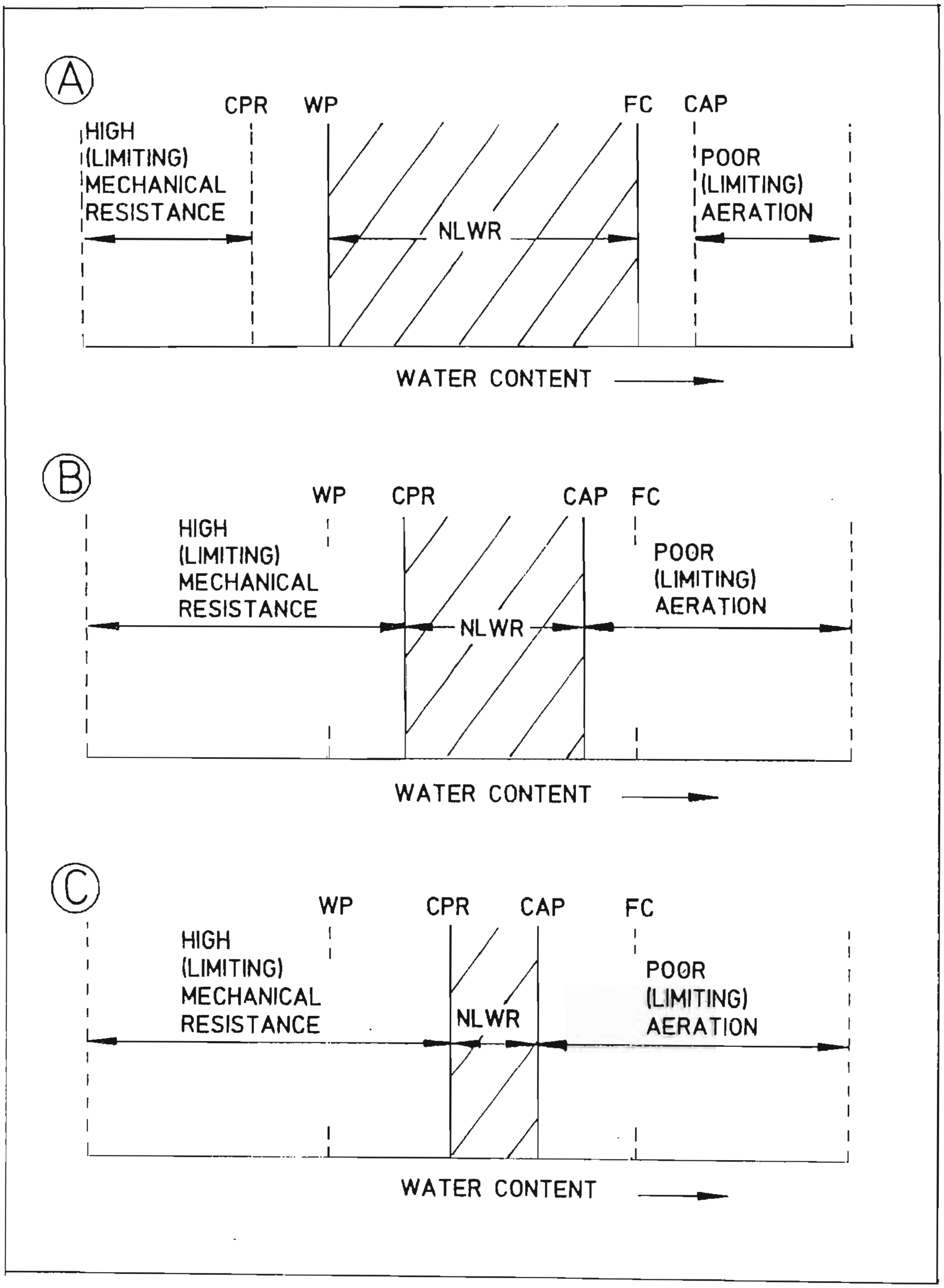


Figure 5.1: Generalised relationship between soil water content and limiting physical properties. The NLWR decreases going from A to C corresponding to an increase in bulk density and poorer soil structure (adapted from Letey, 1985). CPR = critical penetration resistance; FC = field capacity; WP = wilting point; CAP = critical aeration porosity.

The advantage of such a parameter for studies of compaction risk assessment and soil water dynamics under plantation forestry is that the NLWR can be interpreted in conjunction with statistics on temporal and spatial variability in soil water content (Da Silva *et al.,* 1994). Such a measure also conveys information concerning the most appropriate soil management since a primary aim of the land user should be to manage the soil within the NLWR or to improve the NLWR (Letey, 1985). Inappropriate soil and site management usually results in a reduction of the NLWR, through, for example, compaction or incorrect tillage operations.

The definition of NLWR depends upon an adequate description of the upper and lower limits of soil water available to growing plant roots. The upper limit of water available to roots is determined by two factors: firstly, the amount of water in the soil profile following rapid internal drainage of water below the root zone according to the concept of "field capacity", and, secondly inadequate soil aeration which interferes with the biological function of the roots. The lower limit of water availability is defined either by "wilting point" or the water content at which the mechanical resistance of the soil becomes limiting to root penetration. A brief review is presented concerning the principal parameters affecting the upper and lower limits of the NLWR. Factors influencing mechanical impedance of soils will not be discussed here as they were dealt with in detail in the previous chapter.

5.1.1 Aeration

In general, aeration is not believed to be a widespread limiting factor for tree growth in South African forestry soils. Most commercial species suffer considerable growth retardation in soils with high water tables and this factor, combined with government soil conservation laws, results in limited planting close to drainage lines where hydromorphic soils are normally found (ICFR, 1992). Also most forestry soils are well drained oxisols, ultisols, alfisols or entisols which have a dry water regime for much of the year under conditions of plantation forestry (Musto, 1994). Nevertheless, as compaction reduces porosity, critical aeration porosities are reached more easily. An aeration porosity of less than 10% is usually considered limiting for root growth (Vomocil and Flocker, 1961), though some authors have reported higher critical values. Warnaars and Eavis (1972) showed that root growth reduction in pea, corn and grass seedlings was due to oxygen deficiencies when the aeration porosity fell below 25% for a sandy soil. According to Grable and Seimer (1968), the rate of root elongation for corn was reduced considerably when aeration porosities fell below 20% in a silty clay loam.

5.1.2 Field capacity and wilting point

Defining the effects of compaction on field capacity is a complex task. This is partly due to the matric potential corresponding to "field capacity" not being the same for all soils and also that "field capacity" is not expressed consistently in the literature on either a volumetric or a mass basis. In a study of the effects of soil compaction on the water retention of nine Natal soils of various textures Hill and Sumner (1967) grouped water retention curve (WRC) responses to compaction into three categories based on texture: (i) sands, (ii) sandy loams/sandy clay loams, and (iii) clay loams and clays. For sands and clays, compaction increased water retention at constant matric potential. The magnitude of this effect decreased with decreasing matric potentials for sandy soils but increased with decreasing matric potential for clays. For sandy loams and sandy clay loams increasing bulk density resulted in decreased water retention at constant matric potential with the reverse occurring at very low matric potentials. A problem with interpreting the data of Hill and Sumner, (1967) is that their work considered only water retention at matric potentials less than -10 kPa and thus the generally reported "flattening" of the WRC with increasing compaction (Gupta *et al.*, 1989; Katou *et al.*, 1987) was not observed. Also, hysteresis was not taken into account and, as Croney and Coleman (1954) have shown, the effect of compaction is generally to narrow the hysteresis loop.

The influence of bulk density on field capacity, taken as the water content at a matric potential of -5 kPa for a range of British soils, was studied by Archer and Smith (1972) who found that volumetric water content at - 5 kPa increased with increasing compaction until a critical bulk density was reached and then declined rapidly. Archer and Smith (1972) suggested that since wilting point is predominantly controlled by texture, AWC varies in a manner similar to field capacity. Thus a number of optimum bulk densities were identified, corresponding to maximum AWC providing that aeration was not limiting at these bulk densities.

Reeve *et al.* (1973) showed the relationship between bulk density and field capacity, and therefore AWC, to be more complex by considering a wider range of soil textures than those studied by Archer and Smith (1972). Volumetric water content at field capacity, which for all soils was taken as -5 kPa, was found to decrease with increasing compaction. However, for loams and clays field capacity increased with increasing bulk density. Data presented by Bennie and Burger (1988) and Gupta and Larson (1982) showed that the way in which field capacity is modified by compaction is dependent upon the matric potential chosen for field capacity. Bennie and Burger (1979) found that volumetric water content for a fine sandy loam increased with increasing compaction at -10 kPa matric potential but was relatively constant at -5 kPa.

This chapter examines an approach to the assessment of compaction susceptibility by considering the whole range of changes in the air-water-soil matrix brought about by compaction by determining the NLWR of a number of forestry soils for a range of bulk densities. The principal objective of this study was to examine the use of NLWR as an index of compaction risk assessment by obtaining a description of the variation in NLWR with increasing compaction for a number of selected forestry soils. Since limiting values of soil physical properties for tree growth are poorly understood and may change as new research results emerge, an additional aim was to gain an insight into the extent to which the relationship between NLWR and compaction level could be affected by changes in critical growth parameters such as penetration resistance and aeration. It should be emphasised at this stage that the main objective of this chapter was not to establish the effect of bulk density on the WRC in detail but to provide sufficient information on the variation in the WRC parameters, such as field capacity and wilting point, with changing bulk density for a reliable assessment of the changes in NLWR with compaction.

5.2 MATERIALS AND METHODS

5.2.1 Soils

Full water retentivity curves, between saturation and -1500 kPa, were determined for ten selected forestry soils. Water retentivity curves of a further eight forestry soils were carried out down to -100 kPa. The soils were selected to represent a range of textures and organic carbon contents occurring in the main timber growing regions of South Africa. Physical and chemical data of the soils and accompanying site information were presented in Tables 2.1, 2.2 and 2.3.

5.2.2 Sample preparation

For the ten soils on which full water retentivity curves were determined, from saturation to -1500 kPa, the samples were prepared following similar procedures to those of Hill and Sumner (1967) and Mirreh and Ketcheson (1972). Air-dry sieved soil (< 2 mm) soil was used to prepare the soil cores. The mass of soil required to obtain the desired bulk density when compressed into an aluminium cylinder (53.0 mm in diameter and 29.5 mm long) was measured out. The samples were then equilibrated in a plastic bag for two days at water contents approximating the critical water content (CWC_{cmax}) for maximum compressibility as determined in Chapter 3. These were then compressed into the cylinder using an Instron Universal Testing Machine (IUTM). For the higher bulk densities, half of the sample was compressed in two increments. The first half was compressed into the cylinder and then the second half was compressed on top of that. Triplicate cylinders at three or four levels of compaction were established for each soil.

The water retentivity curves of the remaining eight soils were determined down to a matric potential of -100 kPa in the same way as the soils above but were prepared as follows: the required amount of soil was compressed into cylinders 75.0 mm in diameter and 50.0 mm long to achieve a set of samples with three levels of bulk density in duplicate for each soil.

5.2.3 Water retention determination

For the soils on which the full water retentivity curve was determined, water retention was determined at matric potentials of 0, -1.0, -2.5, -5.0, -7.5, -10.0, -33, -100 and -1500 kPa. The same incremental matric potentials were used for the soils on which water retentivity curves were determined only to -100 kPa, with the exception of -1500 kPa.

All the soil cores were saturated with water for several days to ensure as complete a saturation of the soil as possible. As the original weight of air-dry soil was known, together with the dimensions of the core and the hygroscopic water content, it was possible to ascertain when the soil was close to saturation by weighing.

The apparatus used varied for the different equilibrating matric potentials. For high matric potentials the soils were equilibrated on a tension table apparatus consisting of diatomaceous earth over coarse sand (Smith and Thomasson, 1974). Soil water contents were recorded at matric potentials of -1.0, -2.5, -5.0, -7.5 and -10.0 kPa, allowing a minimum of 48 hours for equilibration at each matric potential. For the intermediate range the soil cores were equilibrated at matric potentials of -33 and -100 kPa on a 1 bar ceramic plate in pressure chambers. For very low matric potentials the soil cores were equilibrated at -1500 kPa, corresponding to "wilting point", using 15 bar ceramic plates.

Plant available water capacity (AWC) was determined for each soil as the difference in water content between -10 kPa and -1500 kPa, and readily available water (RAW) between -10 kPa and -100 kPa. The use of -10 kPa as the upper limit of available water (and later for NLWR) was chosen for convenience as Cassel and Nielson (1986) have suggested -10 kPa as an appropriate estimation of field capacity (FC) in the lack of a practical alternative. Local findings support this view (M. Johnson, 1994, personal communication). Porosity was calculated assuming a particle density of 2.65 Mg m^{-3}. Reeve *et al.* (1973) noted that for soils with less than 5% organic carbon the variation in particle density is usually less than 0.1 Mg m^{-3} .

As the water release characteristic (WRC) tends to be S-shaped when plotted on a semi-log scale (Van Genuchten, 1980) a useful indicator of change in compacted soils is the water release index which is the slope at the mid-point of the WRC and is inversely related to pore size uniformity. It may be viewed as the maximum volume of water, expressed in mm m^{-1}, released for a ten-fold decrease in matric potential (O'Sullivan and Ball, 1993). This was estimated graphically from the WRC for all the soils in this study.

5.2.4 Determination of the NLWR

For a particular bulk density the lower limit of the NLWR is either the water content corresponding to wilting point (-1500 kPa) or critical penetration resistance, whichever occurs at the higher water content. The upper limit of the NLWR for a given bulk density is the soil water content at FC or critical aeration porosity, whichever is the drier. The NLWR is expressed in mm m^{-1} or m m^{-1} of water. A conceptual illustration of the NLWR was presented in Figure 5.1. NLWR and AWC were calculated at a particular bulk density or applied pressure from "compaction envelopes". These envelopes were synthesised from the W-P-D diagrams established for the soils in the study (Chapter 2), the PSS - water content - bulk density relationships (Chapter 4) and the water retention parameters evaluated in this chapter.

5.3 RESULTS AND DISCUSSION

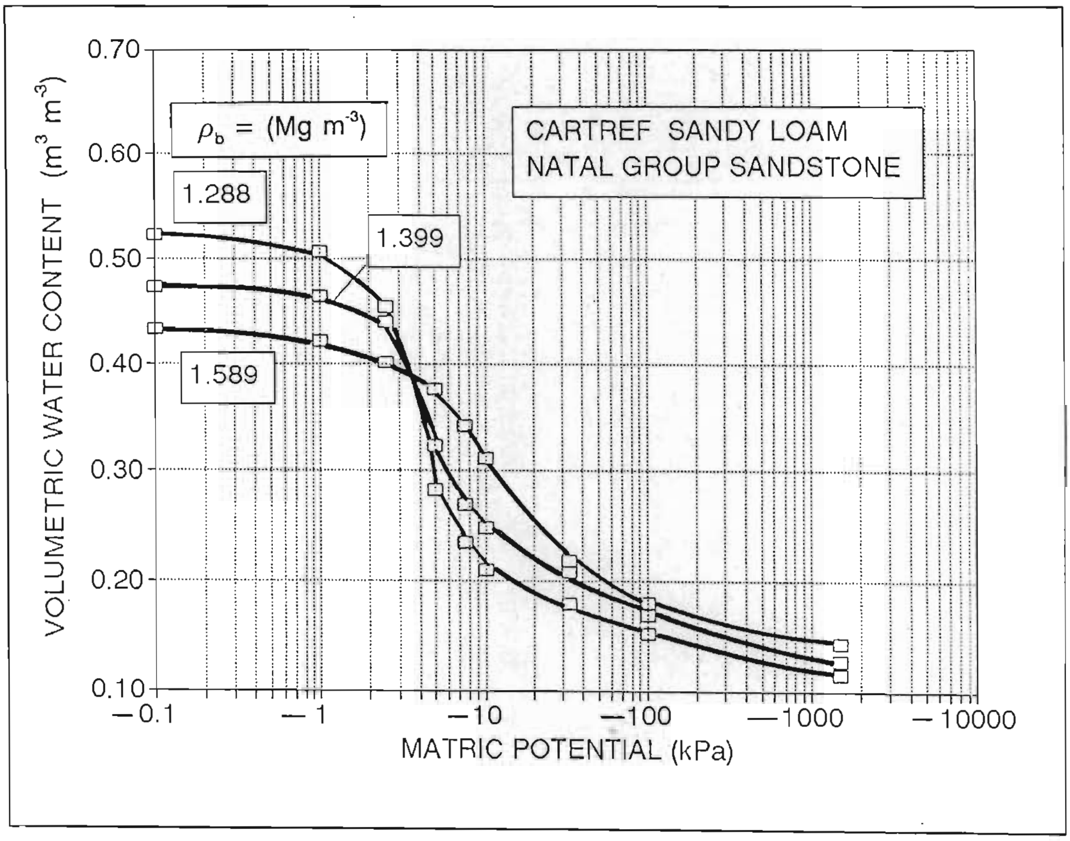
5.3.1 Effect of compaction on water retention characteristics for selected forestry soils

As stated previously, the main objective of assessing the effect of compaction on the WRC was to gain an insight into the factors affecting critical parameters of the NLWR, such as FC, at whatever matric potential it may be defined, and wilting point (-1500 kPa). In order to establish these classical upper and lower limits of available water and to view the effects of compaction on the WRC down to -1500 kPa, water retention parameters were established corresponding to low, medium and high levels of compaction for ten selected forestry soils. Because the effects of compaction on wilting point (-1500 kPa) were comparatively easy to describe and explain, and that the effects of compaction on the water content at the range of matric potentials around FC were far more complex, it was decided to establish water retention parameters for a further eight soils down to -100 kPa.

To illustrate the general effects of compaction on water retention, retentivity curves ranging from saturation to -1500 kPa are presented for six selected soils in Figure 5.2 (a - f). For clarity, water content is expressed on both a mass and a volumetric basis on the WRC curves. Soil water retention parameters for all the soils in this study are given in Tables 5.1 and 5.2. The full water retentivity characteristics of soils in Tables 5.1 and 5.2, which do not appear in Figure 5.2, are presented in Appendix 5.

In general, for all soils, there was a decrease in volumetric and mass water content with increasing compaction until a range of matric potentials was reached, beyond which increasing compaction resulted in an increase in volumetric and mass water content. The reduction in the number of large pores and the resultant increase in mesopores and micropores largely accounts for this effect (Hill and Sumner, 1967). The range of matric potentials at which this "crossover" occurred depended upon soil type but was commonly higher when water content was expressed on a volumetric basis rather than on a mass basis (Tables 1 and 2 and Figure 5.2 (a - f)). Expressed on a volumetric basis, this "crossover" occurs at water contents corresponding to matric potentials of between -2.0 and -10.0 kPa whereas on a mass basis it occurs at a much wider range of matric potentials varying between -4 kPa and -1500 kPa, depending on soil type.

(a) Cartref form (2A)



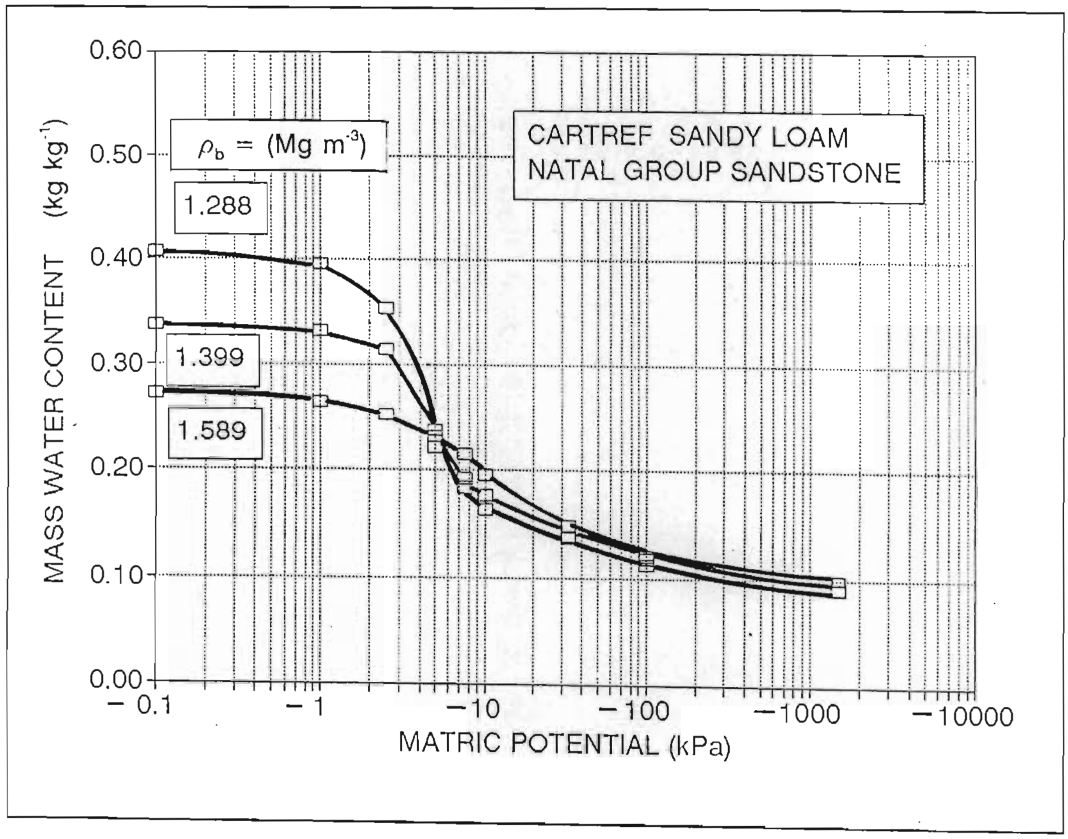
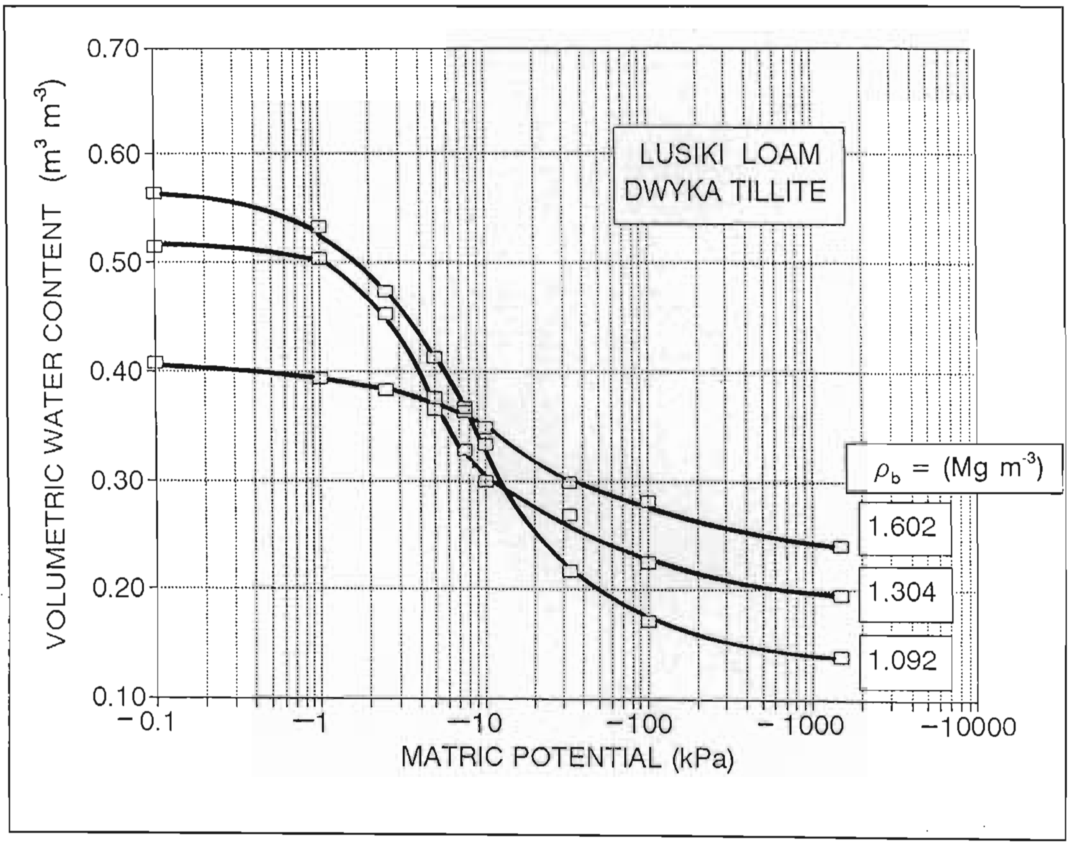


Figure 5.2: Water retentivity curves of selected forestry soils at a range of bulk densities expressed on a volumetric and mass water content basis.

(b) Lusiki form (3A)



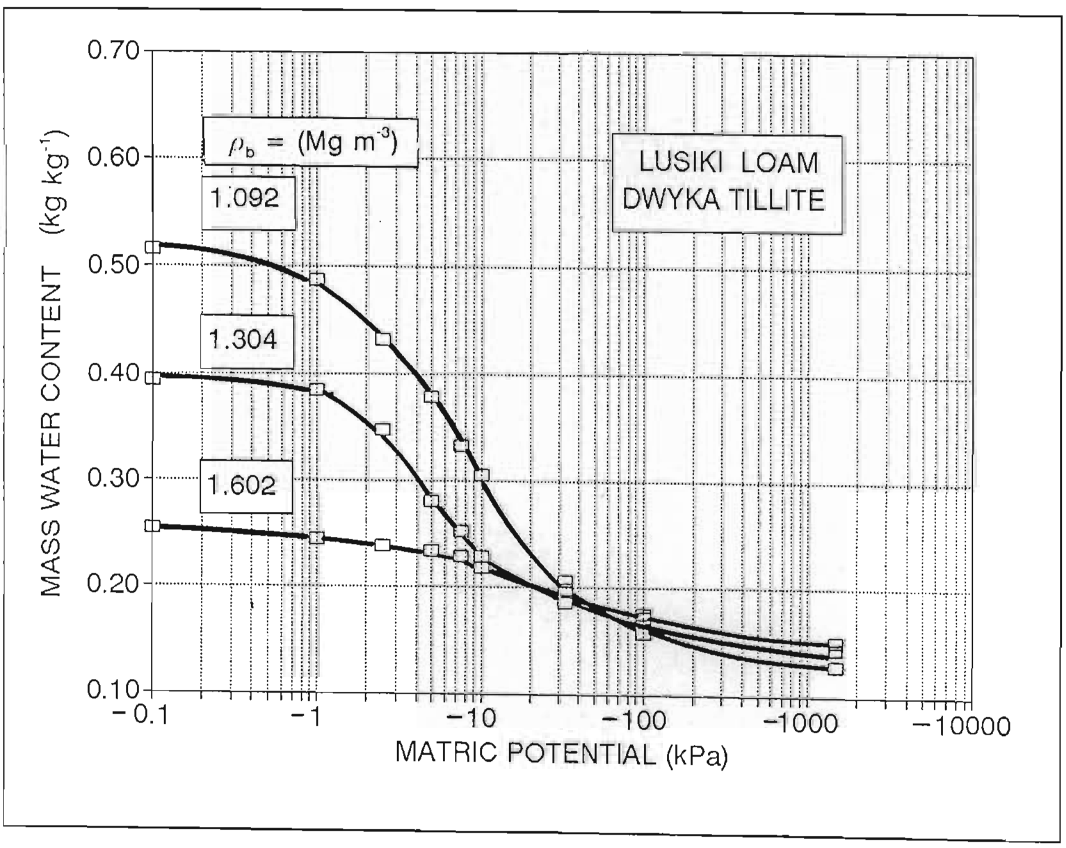
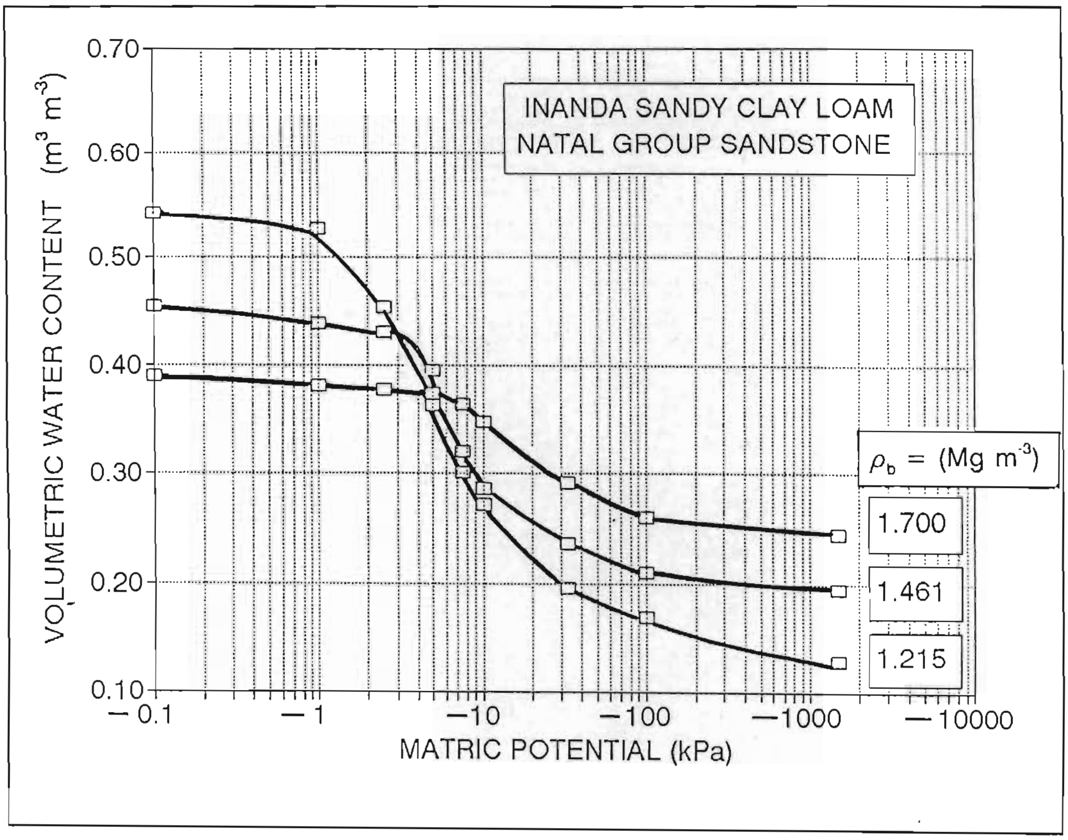


Figure 5.2: (continued)

(c) Inanda form (5A)



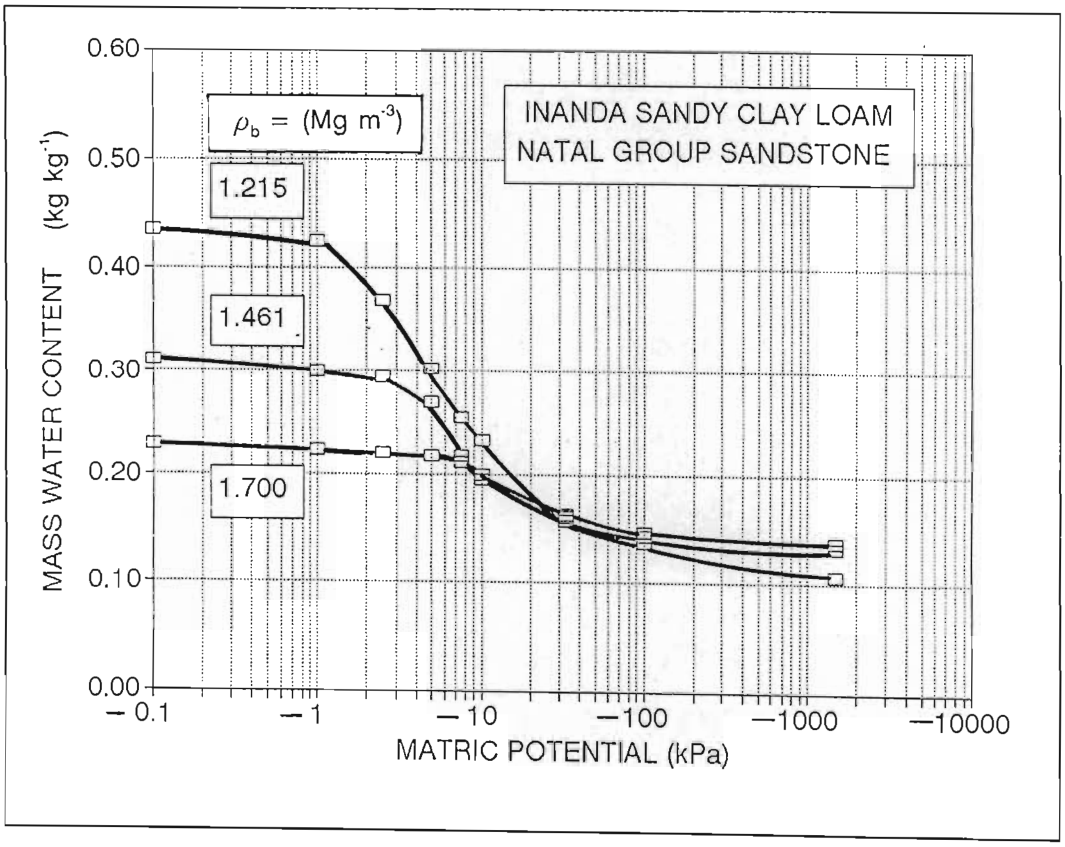
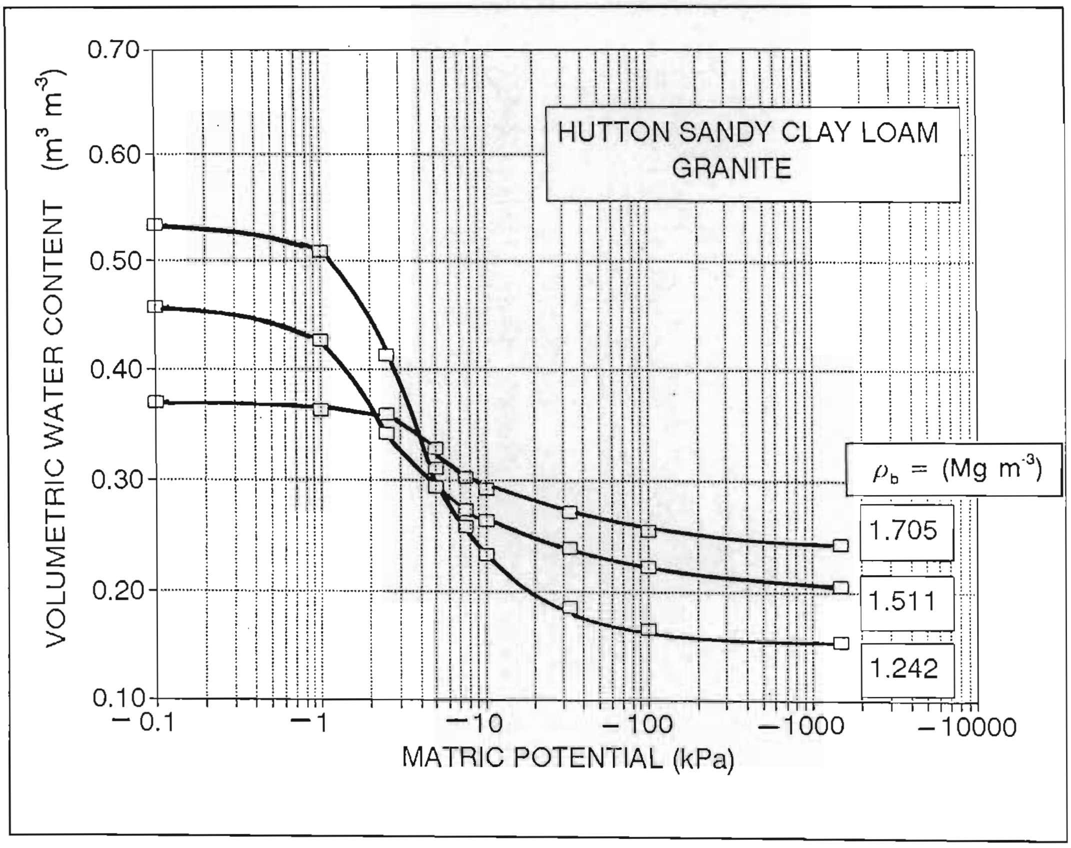


Figure 5.2: (continued)

(d) Hutton form (22A)



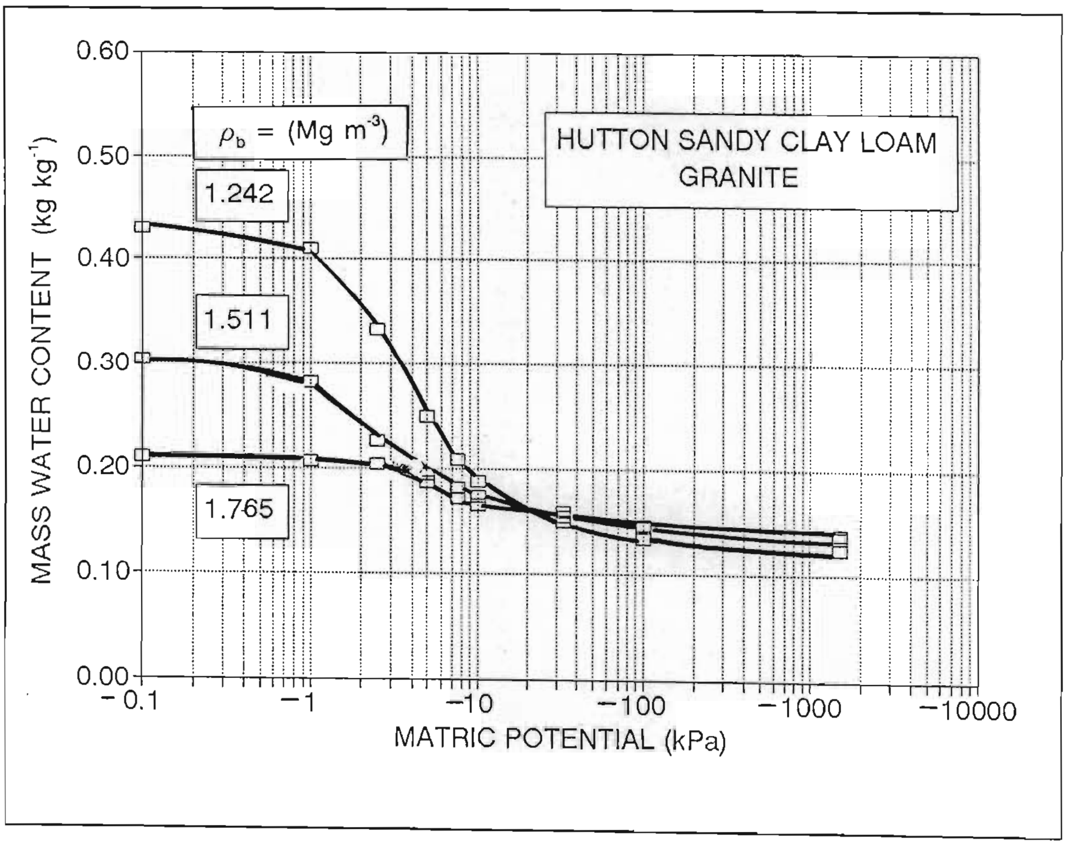
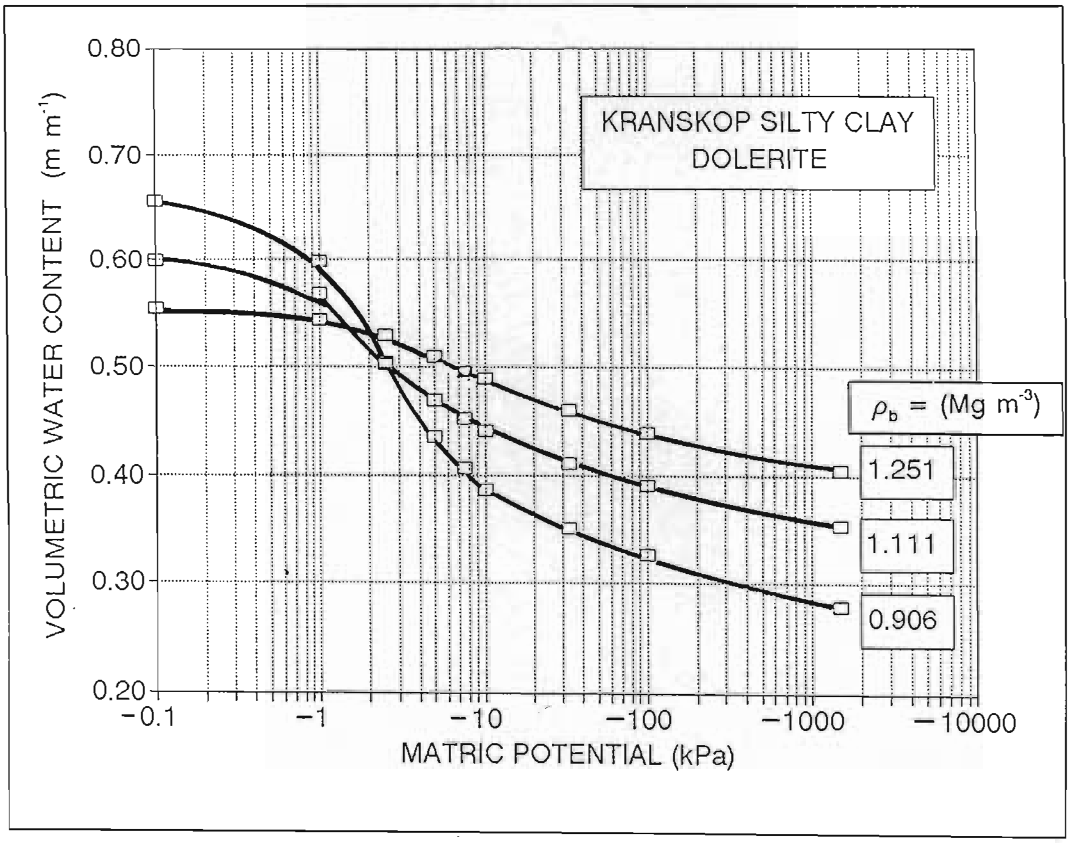


Figure 5.2: (continued)

(e) Kranskop form (6A)



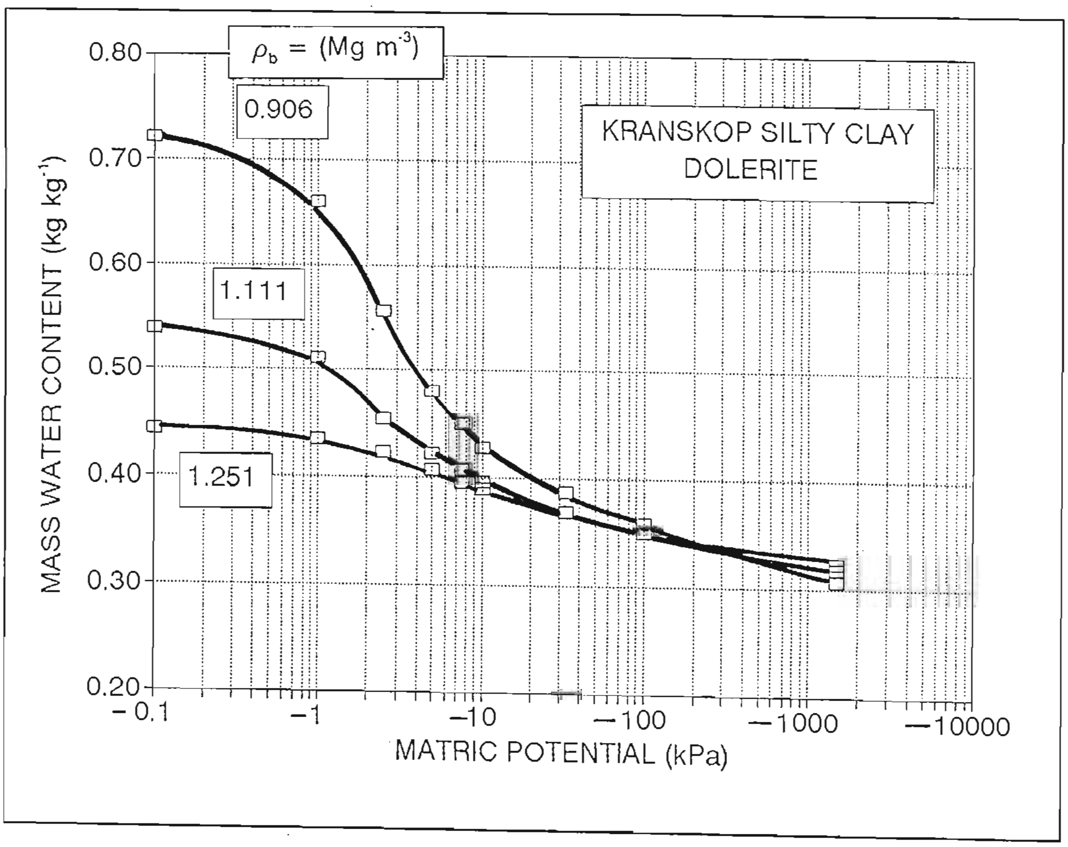
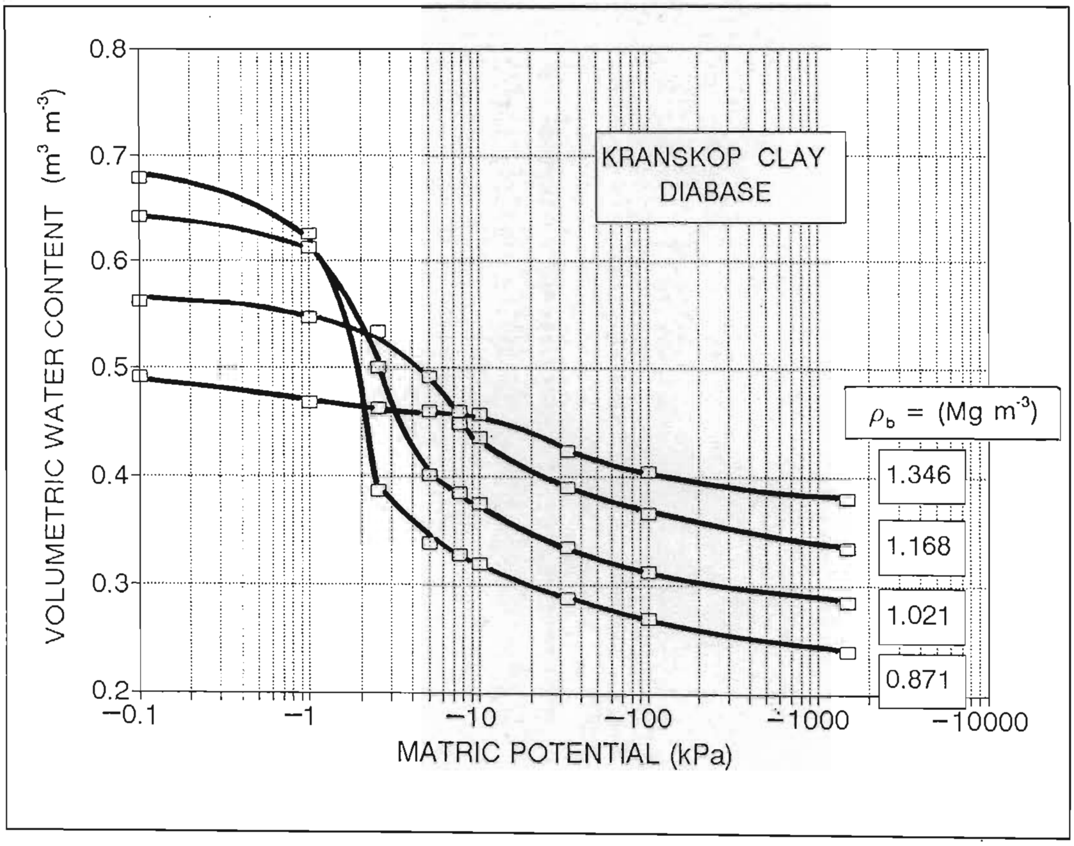


Figure 5.2: (continued)

(f) Kranskop form (19A)



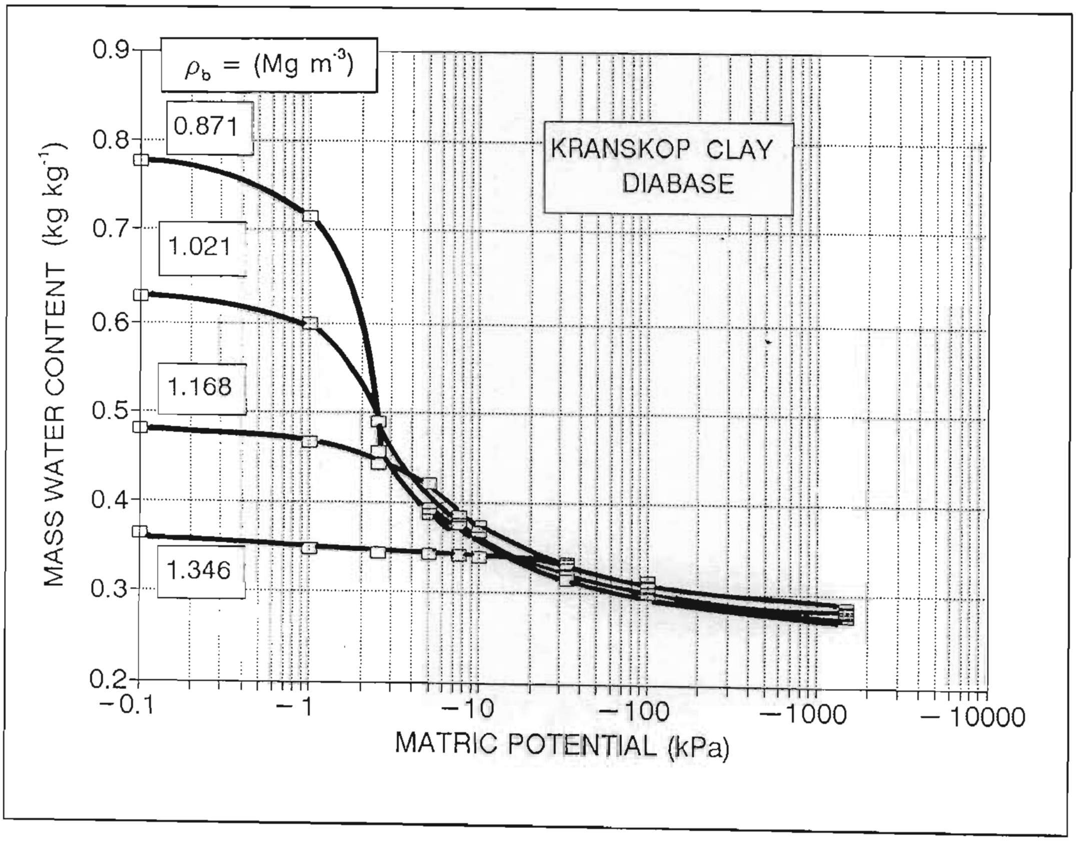


Figure 5.2: (continued)

Table 5.1: Parameters of the water retentivity curve down to -1500 kPa for selected forestry soils at a range of bulk densities.

Soil form Soil texture Site No.	ρ_b Mg m^{-3}	ϕ m^3 m^{-3}	ψ_m = -10 kPa		ψ_m = -100 kPa		ψ_m = -1500 kPa		RAW[a] mm m^{-1}	AWC[b] mm m^{-1}	WRI[c] mm m^{-1}	'Crossover'	
			θ_v m^3 m^{-3}	θ_m kg kg^{-1}	θ_v m^3 m^{-3}	θ_m kg kg^{-1}	θ_v m^3 m^{-3}	θ_m kg kg^{-1}				ψ_{mv} -kPa	ψ_{mm} -kPa
Cf SaLm (2A)	1.284	0.516	0.210	0.164	0.152	0.118	0.116	0.090	58	94	0.530	2 - 5	4 - 6
	1.399	0.472	0.248	0.177	0.168	0.120	0.127	0.091	80	121	0.445		
	1.589	0.400	0.311	0.196	0.179	0.113	0.143	0.090	132	168	0.220		
Lu Lm (3A)	1.092	0.588	0.334	0.306	0.171	0.157	0.139	0.127	163	195	0.310	4 - 10	20 - 200
	1.304	0.508	0.299	0.229	0.225	0.172	0.196	0.150	74	103	0.280		
	1.602	0.395	0.349	0.218	0.281	0.176	0.241	0.150	68	108	0.115		
Kp SiCl (6A)	0.906	0.658	0.387	0.427	0.326	0.360	0.278	0.307	61	109	0.285	1 - 3	200 - 400
	1.111	0.581	0.441	0.397	0.391	0.352	0.354	0.318	50	87	0.180		
	1.251	0.528	0.489	0.390	0.440	0.351	0.405	0.324	48	84	0.075		
No SaClLm (16A)	1.258	0.525	0.228	0.182	0.170	0.135	0.164	0.131	58	64	0.380	2 - 4	4 - 100
	1.515	0.428	0.284	0.188	0.197	0.130	0.196	0.129	87	88	0.190		
	1.757	0.337	0.325	0.185	0.232	0.132	0.230	0.131	93	95	0.145		
Hu SaClLm (22A)	1.242	0.531	0.273	0.188	0.166	0.133	0.154	0.124	67	78	0.415	2 - 7	15 - 30
	1.511	0.430	0.263	0.174	0.222	0.147	0.206	0.136	41	57	0.220		
	1.765	0.334	0.292	0.165	0.256	0.145	0.244	0.138	36	48	0.145		
Ia SaClLm (5A)	1.215	0.542	0.273	0.225	0.168	0.138	0.129	0.106	105	144	0.385	2 - 6	20 - 70
	1.461	0.449	0.286	0.196	0.210	0.143	0.195	0.134	76	91	0.380		
	1.700	0.359	0.347	0.204	0.261	0.154	0.246	0.145	86	101	0.120		

a Readily available water (-10 to -100 kPa)
b Available water capacity (-10 to -1500 kPa)
c Water release index (see text)

ρ_b Bulk density (Mg m^{-3})
θ_v Volumetric water content (m^3 m^{-3})
ψ_m Matric potential (kPa)

ϕ Porosity
θ_m Mass water content (kg kg^{-1})
ψ_{mv} Matric potential (WRC - volumetric basis)
ψ_{mm} Matric potential (WRC - mass basis)

Table 5.1 (continued): Selected parameters of the water retentivity curve down to -1500 kPa for selected forestry soils at a range of bulk densities.

Soil form Soil texture Site No.	ρ_b	ϕ	ψ_m = -10 kPa		ψ_m = -100 kPa		ψ_m = -1500 kPa		RAW[a]	AWC[b]	WRI[c]	'Crossover'	
	Mg m^{-3}	m^3 m^{-3}	θ_v	θ_m	θ_v	θ_m	θ_v	θ_m	mm m^{-1}	mm m^{-1}	mm m^{-1}	ψ_{mv}	ψ_{mm}
			m^3 m^{-3}	kg kg^{-1}	m^3 m^{-3}	kg kg^{-1}	m^3 m^{-3}	kg kg^{-1}				-kPa	-kPa
Cf Lm (10A)	1.352 1.603 1.859	0.490 0.395 0.299	0.326 0.355 0.333	0.242 0.222 0.179	0.173 0.192 0.217	0.128 0.120 0.117	0.126 0.151 0.177	0.093 0.094 0.095	153 163 116	200 204 156	0.185 0.195 0.170	5 - 11	20 - 1500
Hu SaLm (14A)	1.382 1.541 1.789	0.479 0.419 0.326	0.155 0.114 0.115	0.112 0.074 0.064	0.062 0.072 0.089	0.045 0.047 0.050	0.048 0.057 0.072	0.035 0.037 0.040	93 42 26	107 57 43	0.345 0.275 0.220	8 - 40	20 - 500
Kp SaCl (21A)	0.962 1.082 1.255 1.397	0.637 0.591 0.526 0.473	0.241 0.282 0.316 0.366	0.251 0.260 0.252 0.262	0.180 0.217 0.251 0.294	0.187 0.200 0.200 0.210	0.149 0.191 0.233 0.276	0.155 0.177 0.186 0.197	61 65 65 72	92 91 83 90	0.685 0.530 0.335 0.130	2 - 5	2 - 10
Kp Cl (19A)	0.871 1.021 1.168 1.346	0.671 0.615 0.559 0.492	0.319 0.375 0.435 0.456	0.366 0.367 0.373 0.339	0.269 0.312 0.366 0.404	0.308 0.306 0.313 0.300	0.240 0.285 0.334 0.379	0.275 0.280 0.286 0.282	50 63 69 52	79 90 101 77	0.505 0.400 0.205 0.070	2 - 10	2 - 1500

a Readily available water (-10 to -100 kPa)
b Available water capacity (-10 to -1500 kPa)
c Water release index (see text)

ρ_b Bulk density (Mg m^{-3})
ϕ Porosity
θ_v Volumetric water content (m^3 m^{-3})
θ_m Mass water content (kg kg^{-1})
ψ_m Matric potential (kPa)
ψ_{mv} Matric potential (WRC - volumetric basis)
ψ_{mm} Matric potential (WRC - mass basis)

Table 5.2: Selected parameters of the water retentivity curve down to -100 kPa for a range of selected forestry soils at a range of bulk densities.

Soil form Soil texture Site No.	ρ_b	ϕ	ψ_m = -10 kPa		ψ_m = -100 kPa		RAW[a]	WRI[b]	'Crossover'	
	Mg m^{-3}	m3 m^{-3}	θ_v m^3 m^{-3}	θ_m kg kg^{-1}	θ_v m^3 m^{-3}	θ_m kg kg^{-1}	mm m^{-1}	mm m^{-1}	ψ_{mv} -kPa	ψ_{mm} -kPa
No SaClLm	1.215	0.542	0.275	0.226	0.196	0.161	79	0.495	3 - 5	7-12
(9A)	1.395	0.473	0.312	0.224	0.240	0.172	72	0.175		
	1.566	0.409	0.347	0.222	0.295	0.188	52	0.065		
Ia SiClLm	1.096	0.586	0.349	0.319	0.278	0.254	71	0.395	2 - 4	4-6
(8A)	1.242	0.531	0.402	0.324	0.345	0.278	57	0.360		
	1.389	0.476	0.465	0.334	0.406	0.292	59	0.100		
Kp Cl	0.961	0.637	0.365	0.380	0.305	0.317	60	0.496	2 - 4	6-10
(6B)	1.095	0.587	0.421	0.385	0.345	0.315	76	0.230		
	1.228	0.537	0.476	0.388	0.401	0.327	75	0.120		
Kp Cl	1.075	0.594	0.371	0.345	0.282	0.262	89	0.341	3 - 5	4-10
(6B2)	1.219	0.540	0.426	0.350	0.350	0.287	76	0.272		
	1.362	0.486	0.491	0.361	0.440	0.323	51	0.045		
Cf SaLm	1.442	0.456	0.161	0.112	0.115	0.080	46	0.545	4 - 5	4-7
(2E)	1.642	0.380	0.167	0.102	0.139	0.085	28	0.370		
	1.834	0.308	0.180	0.098	0.145	0.079	35	0.280		
Cv SaClLm	1.366	0.484	0.234	0.171	0.175	0.128	59	0.520	3 - 10	4-50
(20A)	1.549	0.415	0.278	0.180	0.208	0.135	70	0.285		
	1.736	0.345	0.298	0.171	0.231	0.133	67	0.120		
Ia SaClLm	1.202	0.546	0.281	0.234	0.180	0.150	101	0.295	1 - 5	4-15
(18A)	1.371	0.483	0.385	0.281	0.247	0.180	138	0.300		
	1.535	0.421	0.431	0.281	0.315	0.206	116	0.155		
Hu SaClLm	1.345	0.493	0.189	0.141	0.129	0.096	60	0.420	1 - 5	2-30
(17A)	1.488	0.439	0.215	0.145	0.159	0.107	56	0.375		
	1.634	0.383	0.224	0.137	0.180	0.110	44	0.155		

a Readily available water (-10 to -100 kPa)
ϕ Porosity
ψ_m Matric potential (kPa)

b Water release index (see text)
θ_v Volumetric water content (m^3 m^{-3})
ψ_{mv} Matric potential (WRC - volumetric basis)

ρ_b Bulk density (Mg m^{-3})
θ_m Mass water content (kg kg^{-1})
ψ_{mm} Matric potential (WRC - mass basis)

This "crossover" range of matric potentials is of particular interest as, on a volumetric basis and with a number of exceptions on a mass basis, it occurs in the range of matric potentials most frequently designated as FC. Since FC designations vary so frequently in the literature, this may explain the uncertain results regarding the effect of bulk density on FC and therefore on AWC. For example, a clear interpretation of the effects of compaction on the AWC of Natal soils (Hill and Sumner, 1967) was difficult as the results were expressed only on a mass basis. However, the expression of results on a mass basis provides a better means with which to examine physical differences in compacted soils (Hill and Sumner, 1967) but this is less useful for practical interpretation. For example, the overall effect of compaction on soil is the reduction in porosity and the conversion of larger pores to smaller pores, the relative importance of these two processes being dependent on soil texture (Hill and Sumner, 1967; Katou *et al.,* 1987). This relationship is demonstrated more meaningfully by the expression of the WRC on a mass basis rather than on a volumetric basis since the influence of bulk density on water content is eliminated.

The data presented in Figure 5.2 (a - f) and in Tables 5.1 and 5.2 indicate that compaction may decrease or increase the FC when the water content is expressed on a mass basis and when FC is assumed to correspond to a matric potential of -10 kPa. This is because the "crossover" of WRCs for different levels of compaction occurred at a wide range of matric potentials, depending on soil type. This range of water contents corresponded to matric potentials of between -2.0 kPa and -1000 kPa. However, no clear pattern of the effect of compaction on water content at -10 kPa with soil type emerged (Tables 5.1 and 5.2).

With the exception of three soils (two loams, 10A and 3A, and one sandy loam, 14A), the effect of compaction generally was to increase the water content at FC on a volumetric basis (Tables 5.1 and 5.2). The reason for this is that increasing compaction results in the "crossover" of the WRCs at various compaction levels within the range of water contents corresponding to -2.0 to -11.0 kPa. In all cases volumetric water content increased with increasing compaction at matric potentials lower than -11.0 kPa.

With increasing compaction only a marginal rise in wilting point (WP) is noted when expressed on a mass basis but a large rise occurs when expressed on a volumetric basis. The contention of Reeve *et al.* (1973) that AWC on a volumetric or depth basis essentially increases with increasing compaction because of the associated rise in FC while WP remains fairly constant, is curious. The data presented here show that although FC increases for most soils with increasing compaction, WP also rises markedly with increasing compaction for each soil in the study when expressed on a volumetric basis. Thus increases in AWC (mm m^{-1}) caused by increases in FC were offset by increases in wilting point.

Table 5.1 shows that the water release index (WRI) decreased substantially with increasing compaction. In other words the slope of the central portion of the WRC decreased with increasing bulk density (Figure 5.2, (a - f)). This decrease in WRI corresponds to a decrease in large pore sizes which may have the effect of substantially lowering infiltration rates (Akram and Kemper, 1979). O'Sullivan and Ball (1993) also reported a noticeable decrease in WRI for a limited number of topsoils from field experiments in Scotland. Although O'Sullivan and Ball (1993) suggested that this was a sensitive indicator of changes in soil structure, as supported by the data in this study, it is not clear what practical value the water release index has, if any, for plant growth. The importance of the WRI with respect to plant growth is unclear since it consistently decreases with increasing compaction whereas AWC increases or decreases with increasing compaction level. Although large transmission pores are lost during compaction many are converted into mesopores in the available range. This is reflected by the "shoulder" of the S- curve being moved to the right with increasing compaction (for example Figure 5.2 (a - f)).

Due to the small range of bulk densities covered per soil, a clear effect of compaction on AWC, expressed in mm m^{-1}, was difficult to ascertain precisely. Table 5.1 shows that increasing compaction lowered AWC for most soils. Of the ten soils studied only three showed an increase in AWC following an increase in compaction. All three soils showed an increase in AWC up to a certain bulk density after which AWC declined which is similar to the behaviour reported by Archer and Smith, (1972) and Reeve *et al.* (1973). Tables 5.1 and 5.2 show that if all the soils are considered, compaction has a similar effect on readily available water (RAW) for only 4 out of 18 of the soils in this study, i.e. an increase with increasing compaction and then a decline with further compaction. Clearly, for these soils, moderate compaction converts many of the larger pores in the unavailable range (> -10 kPa) into smaller pores in the available range.

5.3.2 The effect of compaction on the Non-Limiting Water Range (NLWR)

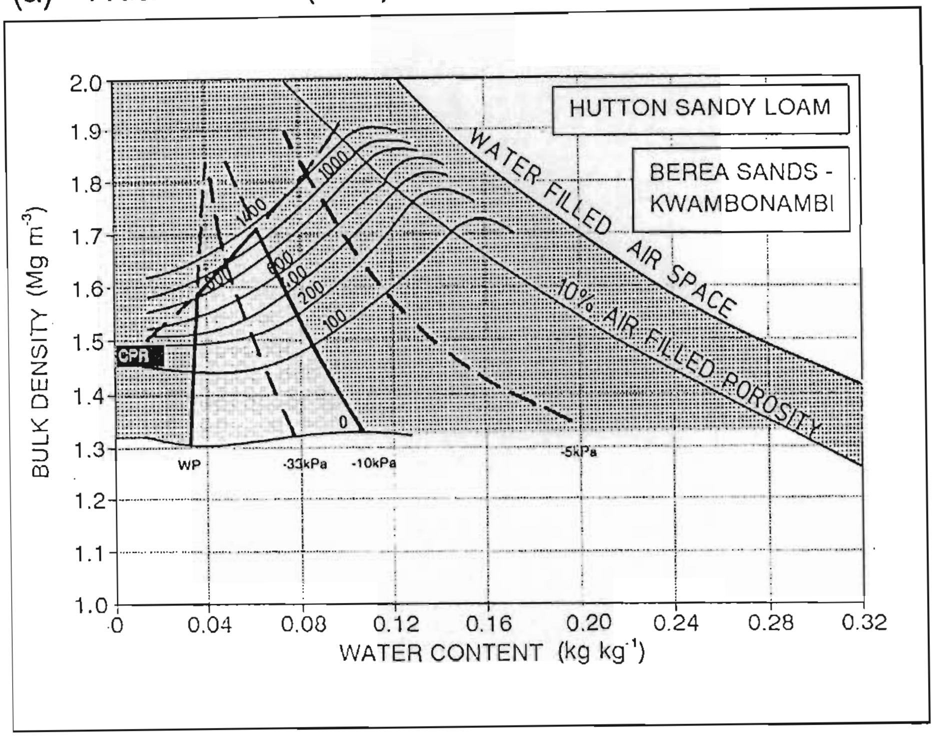
5.3.2.1 Compaction envelopes

In this study the concept of the "compaction envelope" was developed to illustrate the entire range of changes taking place in the soil - water - air matrix following compaction and to provide a link between causes and effects of compaction. Compaction envelopes were evaluated by superimposing critical values of soil physical properties defining excessive compaction on the water-pressure-density (WPD) diagrams which were derived in Chapter 2. The critical values chosen were 2 MPa for mechanical resistance seriously limiting tree root development (Graecen and Sands, 1980), 10% air filled porosity critical for gaseous diffusion (Vomocil and Flocker, 1961) and -1500 kPa for wilting point. For comparative purposes, the relationships between mass water content and bulk density at three matric potentials are shown in the compaction envelopes (Figure 5.3 (a - h)). These water contents corresponded to -5 kPa, -10 kPa and -33 kPa and allowed determination of the effect of different field capacity definitions on the NLWR. The penetrometer soil strength - bulk density - water content relationships that were established in Chapter 4 for each soil were used for the 2 MPa critical penetration relationship.

Figure 5.3 shows compaction envelopes for eight selected forestry soils of varying texture and underlying geology. These envelopes were subsequently used to calculate the NLWR at a range of relative bulk densities and applied pressures. The compaction envelopes are essentially a synthesis of all the inter-relationships studied so far and it is proposed that they are realistic representations of the potential effects of compaction on soil physical quality because the envelopes enable factors influencing the compaction process and the properties resulting from compaction to be represented in one diagram. As well as being able to calculate the NLWR directly, the envelopes also allow flexibility in calculating the NLWR if, for example, critical parameters differ for different tree or plant species or change with advances in research.

A feature of the envelopes is that it is possible to immediately identify the optimum bulk densities and water contents in which roots will enjoy optimum growth conditions free from major physical constraints. Together with the iso-stress lines derived from the W-P-D diagrams in Chapter 2, the envelopes provide a means for a rapid assessment of the ease with which these optimum conditions may deteriorate due to compaction. A feature of all the compaction envelopes in Figure 5.3 is that the range of optimum water contents is bounded on the left, or drier end, by the wilting

(a) Hutton form (14A)



(b) Cartref form (10A)

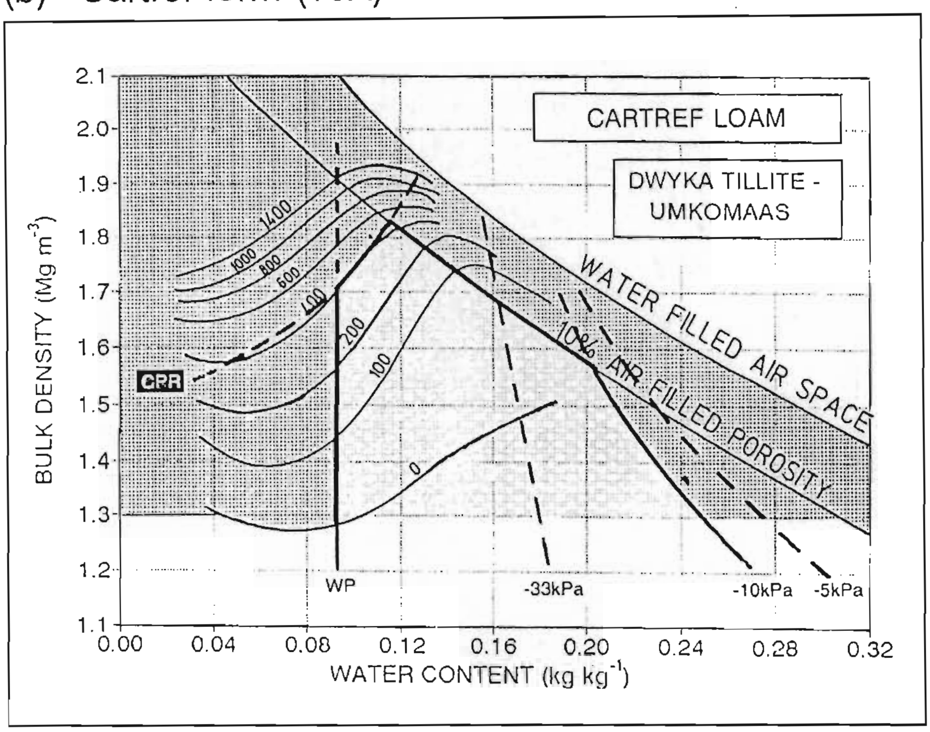
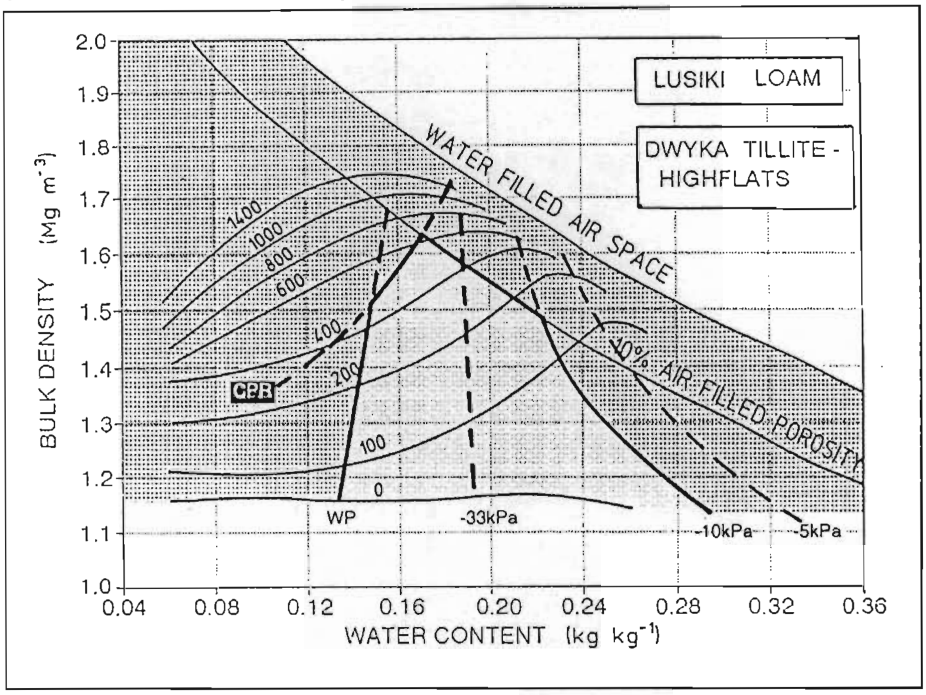


Figure 5.3: Compaction envelopes for a range of selected forestry soils, showing the relationship between water content, bulk density and critical NLWR parameters of field capacity (-10 kPa and -5 kPa), wilting point (-1500 kPa), critical penetration resistance (2 MPa) (CPR) and critical aeration porosity (10%). The lightly hatched area within the solid lines indicates bulk densities and water contents within the NLWR.

(c) Lusiki loam (3A)



(d) Inanda form (5A)

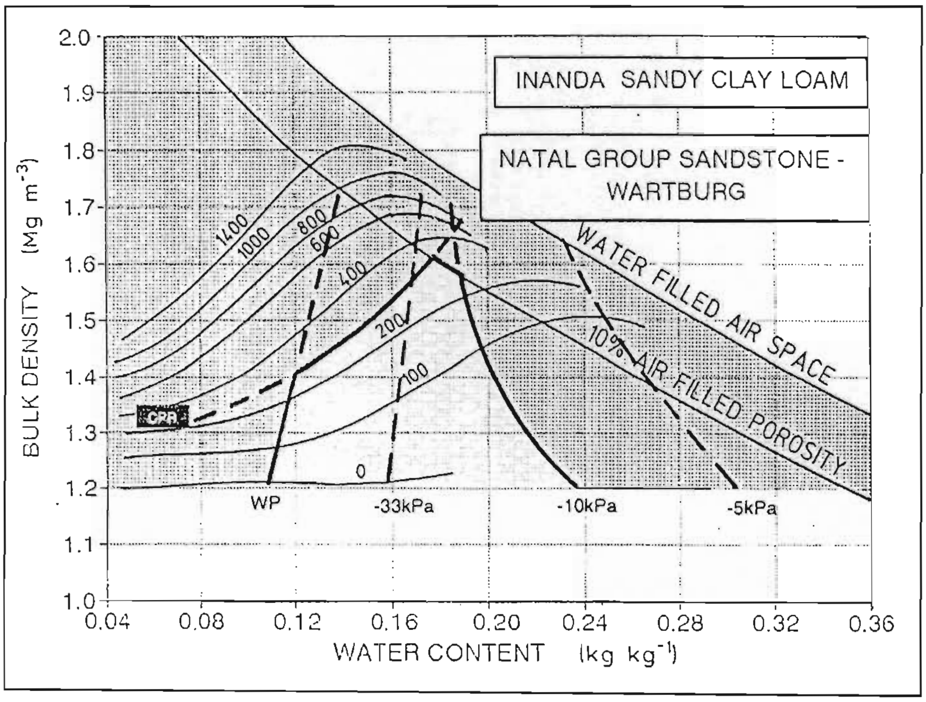
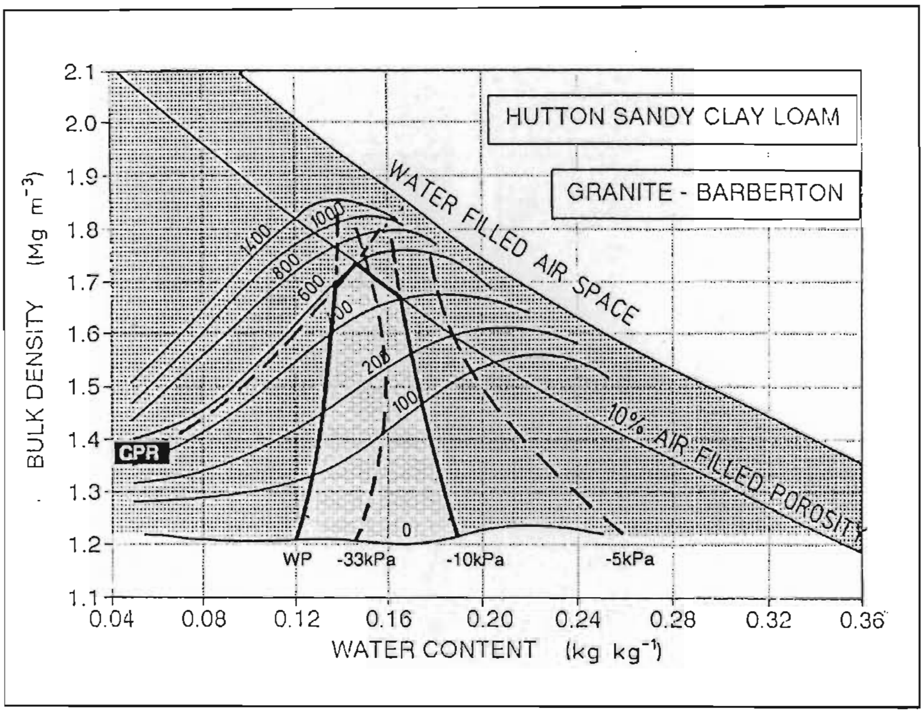


Figure 5.3: (continued)

(e) Hutton form (22A)



(f) Kranskop form (21A)

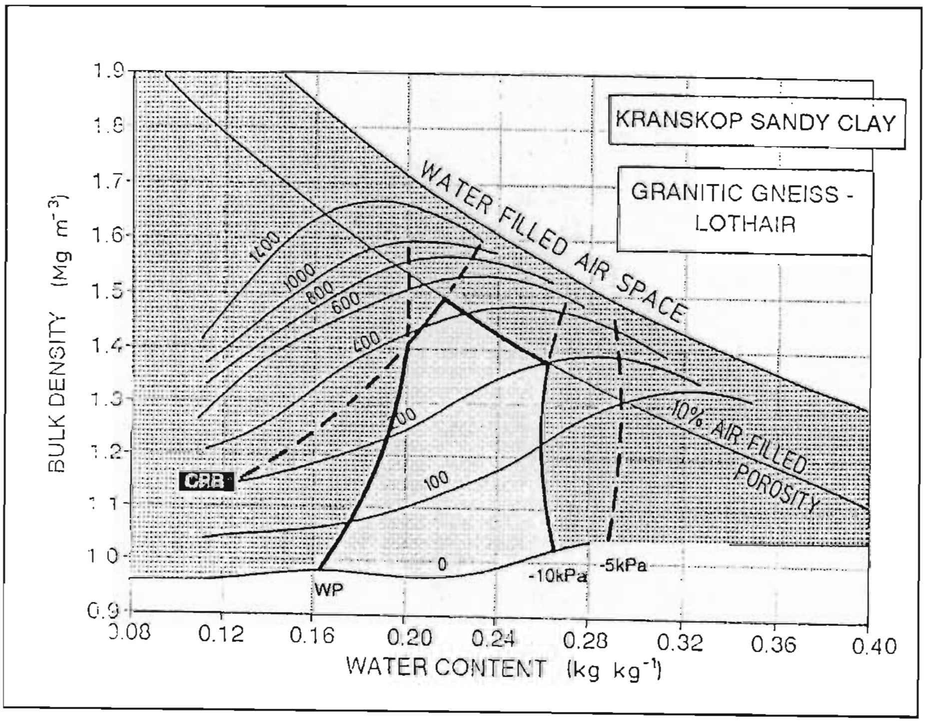
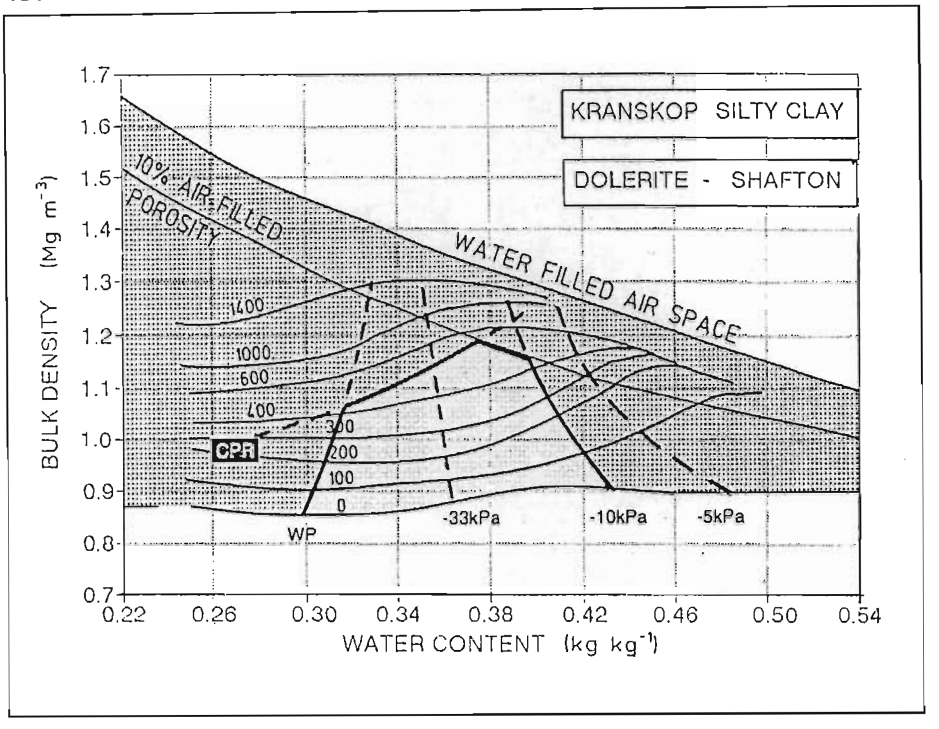


Figure 5.3: (continued)

(g) Kranskop form (6A)



(h) Kranskop form (19A)

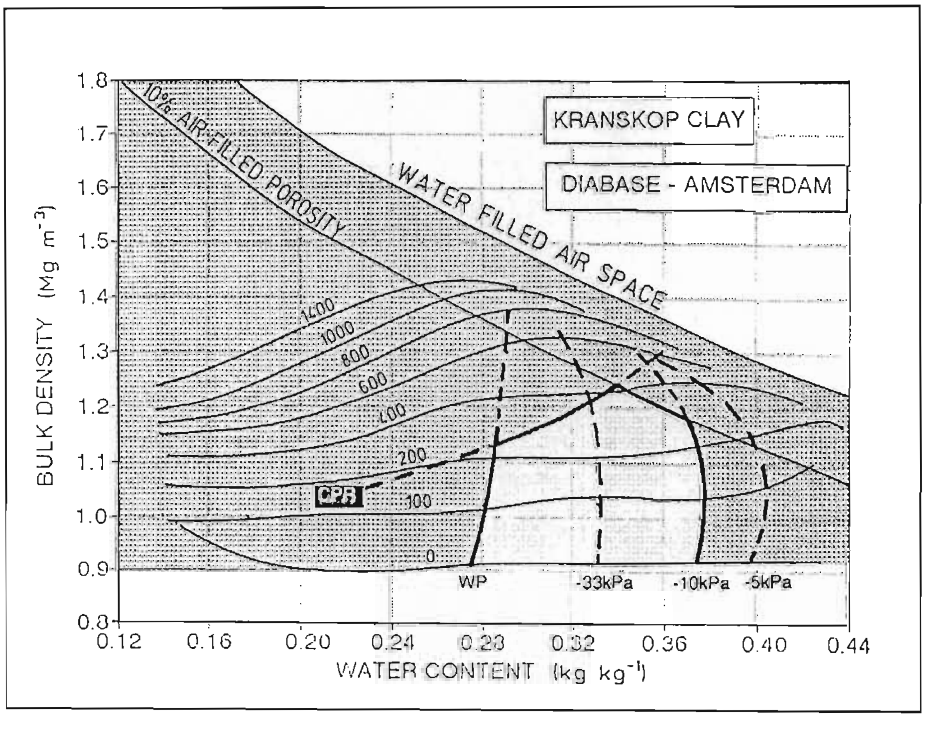


Figure 5.3: (continued)

point or, as compaction level increases, by critical penetration resistance. On the right hand side of the envelopes, i.e. the wetter end, the range of optimum water contents is bounded by FC or, as compaction increases, critical air-filled porosity.

Regardless of the soils' inherent physical condition, usually reflected in the AWC for that soil, the envelopes provided a means with which to assess potential changes in the NLWR with increases in compactive effort, in this case illustrated by iso-stress lines. Usually the more iso-stress lines within the lower portion of the envelope, the more resistant the soil will be with respect to changes in the air-soil-water matrix. Thus the compaction envelopes for the Hutton sandy loam and the Kranskop sandy clay (Figures 5.3a and g, respectively) reflect a large compactive effort required before major changes in the NLWR occur. It is interesting to note that these soils have moderately low compression indices (0.248 and 0.389 respectively; Chapter 3, Table 3.2). On the other hand the Lusiki loam and the Inanda sandy clay loam (Figures 5.3c and d, respectively) possess a large initial AWC or NLWR but this rapidly decreases with only moderate increases in compactive effort. It is no coincidence that these soils have moderately high compression indices (0.444 and 0.456 respectively, Chapter 3, Table 3.2).

For all the soils in Figure 5.3, the NLWR has the same value as the AWC at relatively low bulk densities, i.e. the limits as classically defined by FC and WP. If -10 kPa is taken as FC, then for all of the soils in Figure 5.3 the upper limit of the NLWR will be defined by FC at low bulk densities and then by critical aeration porosity with increasing compaction. The lower limit of the NLWR will be defined by wilting point at low bulk densities and by penetration resistance at higher levels of compaction. Topp *et al.* (1994) found that the lower limit of the NLWR was consistently defined by a CPR value of 2 MPa, even at low bulk densities, for a range of Canadian soils.

A feature of the compaction envelopes in Figure 5.3 (a - h), with the exception of the Cartref loam (Figure 5.3b), is that penetration resistance usually defines the lower limit of the NLWR at about the same or lower bulk density than when aeration porosity defines the upper limit. This is perhaps to be expected since most of the soils in this study show well drained characteristics. However, if -5 kPa is designated as FC, as bulk density increases aeration porosity defines the upper limit of the NLWR at about the same compaction level or less than penetration resistance defines the upper limit. In the case of the Lusiki loam, which has a large AWC, aeration becomes limiting relatively quickly with increasing compaction if - 5 kPa is designated as FC (Figure 5.3c). Archer and Smith (1972) and Agrawal (1991) have suggested that an understanding of this dynamic is an important consideration in soil management strategies. For example, they showed that AWC of droughty sandy soils could be improved by compaction providing air-capacity was not reduced to critical levels. Close inspection of the compaction envelopes in this study elicit some interesting soil characteristics which affect soil management and are manifest in the soils' morphology. For example it was mentioned previously that critical aeration porosity affected the upper limit of the NLWR of the Cartref loam in Figure 5.3b at lower bulk densities than CPR affected the lower limit with increasing compaction. A similar situation was obtained with the Lusiki loam (Figure 5.3c). If FC is defined at matric potentials slightly higher than -10 kPa, which is possible for these soils since they both have poorly drained subsoils (see Appendix 1), then inspection of the compaction envelopes for both these soils (Figure 5.3b and c) reveal a considerable susceptibility to aeration problems. This is borne out by the greyish colour of both these soils and infrequent mottling even of the topsoil. In the case of the Cartref loam which is also prone to slumping (see 0 kPa iso-stress line in Figure 5.3b) the aeration problems are likely to be quite serious even without considerable compaction by vehicles. It is commonly believed that hardsetting and development of high levels of soil strength are the factors most limiting to management of both these soils but the data presented here show that aeration problems are at least as limiting as high levels of soil strength to root growth.

The compaction envelope of the Hutton sandy loam (Figure 5.3a) also conveys interesting information about the water relations of these soils. Many deep red soils developed on old dune cordon sandstone in Zululand, northern KwaZulu-Natal, have recently been afforested and it is frequently observed that these soils are wet or close to field capacity for long periods during the year (Smith, 1991) yet there are no signs of aeration problems in the soils (deep red, single grain sandy loams). Figure 5.3a shows that even at high levels of compaction aeration is not a limiting factor and that for aeration to become a problem for root growth compaction levels near the MBD of this soil (1.96 Mg m^{-3}) would have to be attained. Alternatively, aeration would only become a problem if FC was at a matric potential considerably higher than -5.0 kPa or critical aeration porosity increased to over 30%.

5.3.2.2 The potential effects of changes in critical growth parameters on the NLWR

The compaction envelopes also allow an appraisal of the relative importance of the various parameters which define soil physical limitations. As a critical penetration resistance of 2 MPa only affects the upper left portion of the compaction envelope, a change in critical resistance to 3 MPa would result in changes to the NLWR, depending on soil type. For example, changes in CPR from 2 MPa to 3 MPa would be of little significance to the Hutton sandy clay loam and the Lusiki loam (Figure 5.3a and c, respectively) as wilting point is the controlling upper limit right up to very high levels of compaction. A change in CPR to 3 MPa for these soils would take the CPR out of the compaction envelope and the lower limit of the NLWR would continue to be defined by wilting point even at high levels of compaction. Changes in CPR would be of more relevance to soils such as the Inanda sandy clay loam, Kranskop silty clay and Kranskop clay (Figure 5.3d, g and h, respectively) where penetration resistance becomes limiting before wilting point even at moderate levels of compaction. An increase in CPR to 3 MPa for these soils would result in a large increase in NLWR at higher levels of compaction. On the other hand, the growth of crop or tree species with low root tolerances to mechanical impedance could be hindered when growing in soils where the lower limit of the NLWR is defined by CPR for higher levels of compaction, for example the Inanda sandy clay loam, Kranskop silty clay and Kranskop clay (Figure 5.3d, g and h).

The importance of changes in critical growth parameters on the NLWR is very dependent upon soil type. Changes in critical aeration porosity would have little effect on the Hutton sandy loam (Figures 5.3a) at any compaction level and only at high levels of relative compaction for the Kranskop silty clay (Figure 5.3g) and the Kranskop clay (Figure 5.3h). Even small increases in critical aeration porosity would have the greatest effect on soils with high AWC values such as the Lusiki loam (Figure 5.3c). Increases in critical aeration porosity to 15%, for example, would have a considerable effect on the NLWR especially with respect to soils which have compaction envelopes close to critical aeration porosity, such as the Cartref loam and Lusiki loam in Figure 5.3b and c. The effect of a lower threshold of aeration porosity on the NLWR would be even more pronounced should FC be taken at higher matric potentials than -10 kPa.

An important feature of the WRC, which is well illustrated by the compaction envelopes and the previous work on water retention is that small changes in the designated matric potential for FC may result in a large change in AWC, and by implication NLWR, at all levels of compaction. This effect varies depending on soil type but is nevertheless an important consideration. Furthermore, as implied earlier, the higher the designated matric potential for FC the more important the changes in critical aeration porosity become for certain soils. For example, in the case of the Inanda sandy clay loam (Figure 5.3d), the higher the matric potential chosen for FC the more susceptible the soil is to aeration problems. If -5.0 kPa was designated as FC then this soil, despite having a large AWC and NLWR, critical aeration porosities would be reached more rapidly for only small increases in bulk density.

As the designated matric potential for wilting point, -1500 kPa, occurs on a very level portion of the WRC, changes in wilting point criteria will have little impact on the lower limit of the NLWR. As the WRC becomes flatter with increasing compaction, very little water is available in the classical sense at matric potentials much lower than - 300 kPa. Thus any change in the designated matric potential for wilting point would have to be fairly substantial to have any major impact on water availability, more so with increasing compaction. This point was also made by Ohu *et al.* (1985) who reported that little or no water was available for plant extraction below matric potentials of -500 kPa in a range of compacted soils of varying texture and organic matter contents, even though the volumetric water content of the soil was still large. It is likely that current research efforts underway to locate the lower limit of water extraction by trees would make a greater contribution to the understanding of the NLWR (and AWC) for tree species, and hence a better basis for discerning site productivity potential, by concentrating on the upper limit.

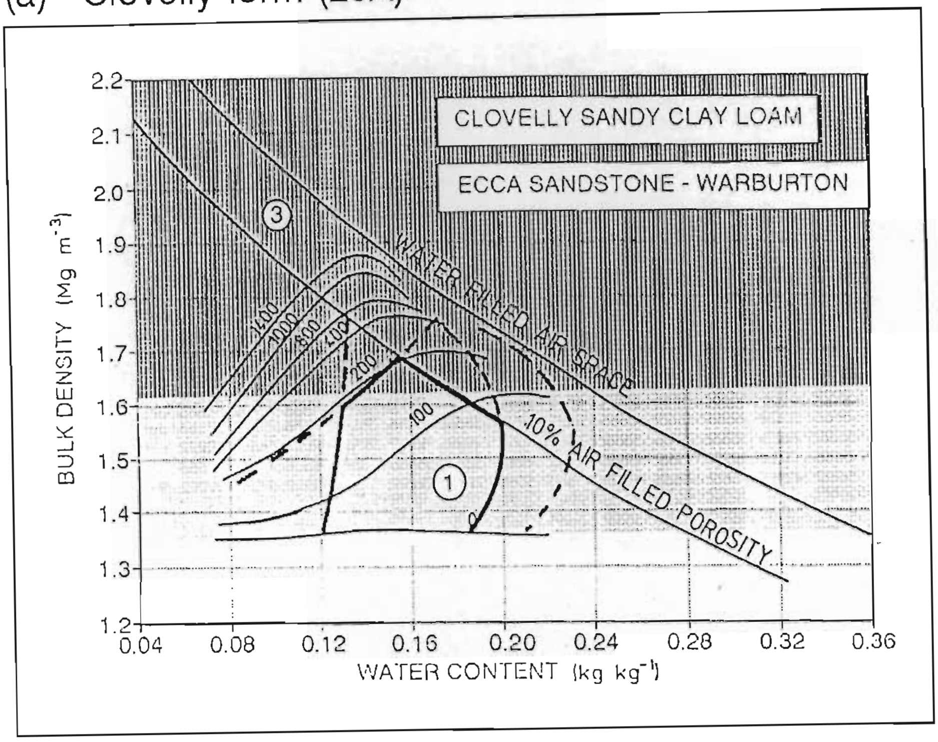
5.3.2.3 Practical interpretation of compaction envelopes

The compaction envelopes enable the determination of the range of applied pressures and water contents that affect the level of soil compaction corresponding to changes in the NLWR. These are indicated by Zones 1 to 3 in Figure 5.4 for two selected soils which are used as examples. For practical purposes it is proposed that the compaction envelopes enable the separation of different levels of compaction into *acceptable*, *moderate* and *excessive compaction*, are based on changes in NLWR. It must be emphasised that the limits chosen below are entirely arbitrary and serve merely to illustrate the potential practical interpretation of the compaction envelopes.

Zone 1: **Acceptable Compaction**: Applied pressures and water contents resulting in compaction levels in this zone cause either small increases or decreases in NLWR. Any decrease is usually less than 20% of the NLWR of the soils' normal field bulk density and these changes are not considered to affect root or plant growth.

Zone 2: **Moderate Compaction**: Applied pressures and water contents resulting in compaction levels in this zone cause a decrease in NLWR of more than 20% over the uncompacted NLWR provided the NLWR does not fall below 50 mm m^{-1}. Soil physical properties in this zone are considered moderately limiting to root or plant growth.

(a) Clovelly form (20A)



(b) Kranskop form (21A)

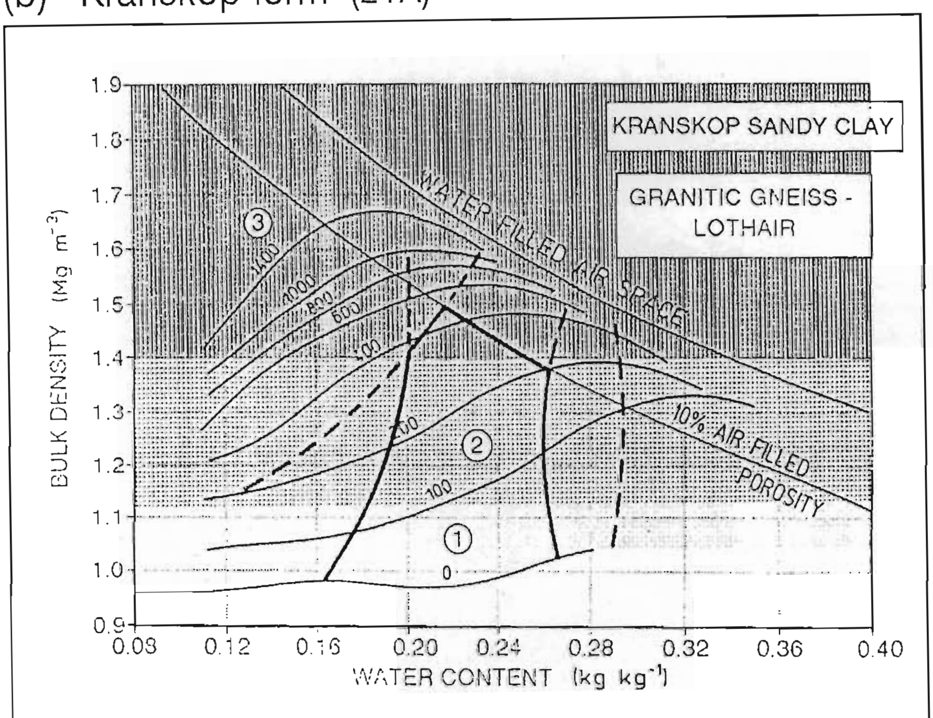


Figure 5.4: Practical interpretation of compaction envelopes for (a) Clovelly sandy clay loam and (b) Kranskop sandy clay. 1 = acceptable compaction; 2 = moderate compaction; 3 = excessive compaction (see text for full explanation)

Zone 3: **Excessive Compaction**: Applied pressures and water contents resulting in compaction levels in this zone result in NLWR values of less than 50 mm m^{-1} which are considered severely restricting to root or plant growth.

In the case of the Clovelly sandy clay loam, only two compaction categories are represented (Figure 5.4a). The cut off between acceptable and excessive compaction is abrupt and is due to the small NLWR at uncompacted bulk densities. Thus the decrease in NLWR with increasing compaction only exceeds 20% when the soil reaches the critical NLWR for excessive compaction of 50 mm m^{-1}. This will commonly be the case when a soil normally has a low NLWR. In the case of the Kranskop sandy clay, relatively low ground pressures (< 150 kPa) for a wide range of water contents result in moderate compaction levels being reached relatively rapidly, but considerably higher ground pressures, particularly when the soil is dry, are required to cause excessive compaction (Figure 5.4b). A feature of both the compaction envelopes in Figure 5.4 is that excessive compaction only becomes a problem at bulk densities where critical penetration resistance and aeration porosities define the upper and lower limits of the NLWR. An examination of Figure 5.3 (a - f) reveals that this would also be the case for most of the soils represented.

5.3.2.4 The effect of relative bulk density (RBD) on the NLWR

Relationships between NLWR and relative bulk density for a number of forestry soils are presented in Figure 5.5. The soils were chosen to represent a wide range of soil textural groupings, ranging from a loamy sand to a clay. Where two soils represent a particular textural group, one has a high organic carbon content (denoted by the letter h following the textural abbreviation) and the other has a low organic carbon content. For convenience, this division corresponds to the humic and orthic horizon division (1.8% organic carbon content by Walkley-Black) of the South African classification system (South African Soil Classification Working Group, 1991). It should be noted that as there was a limited number of soils available in the study, the soil chosen for each textural class was used as an example. Although it is likely that these relationships reflect other soils' behaviour of that particular textural class, the results should not necessarily be regarded as "average".

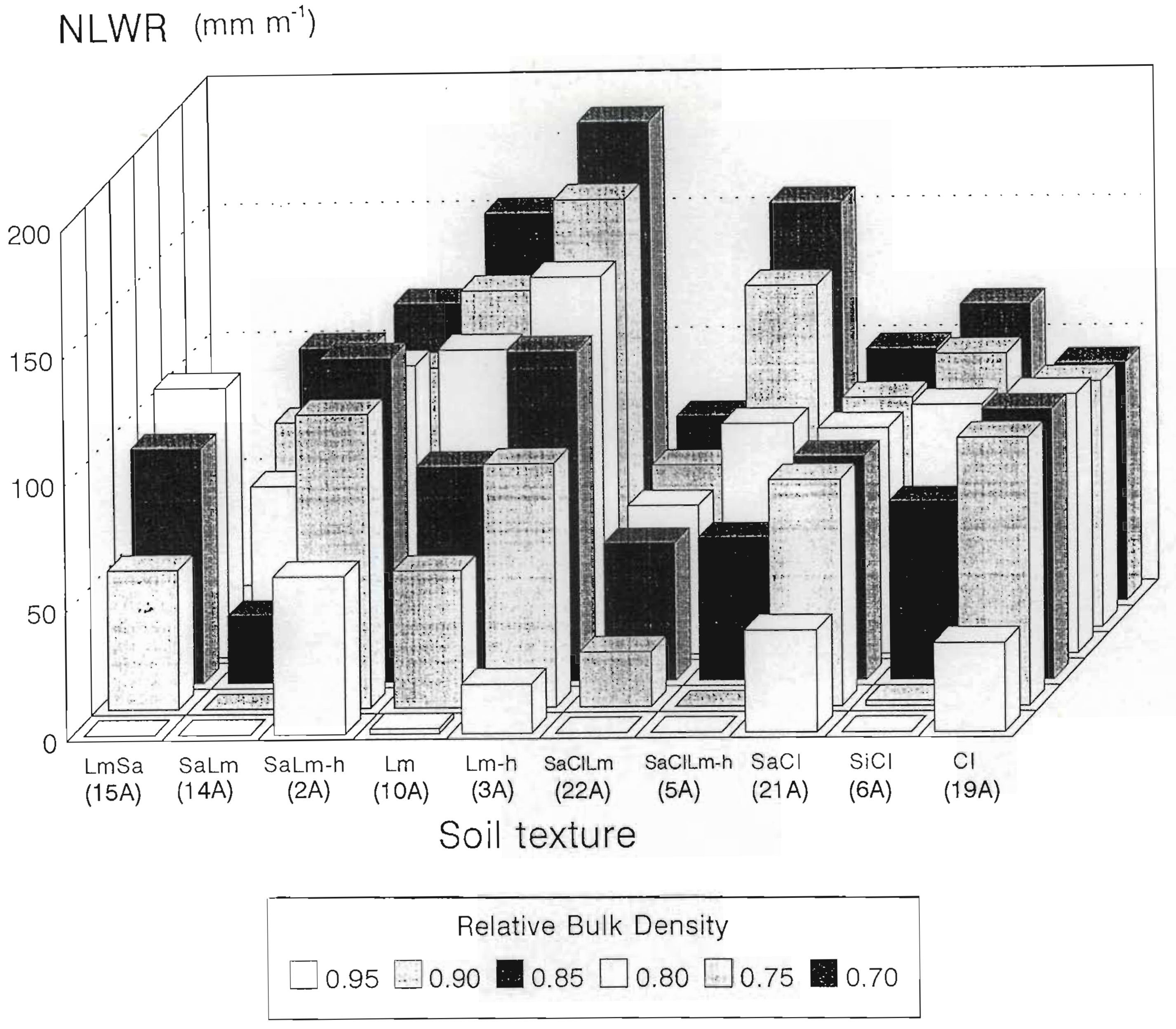


Figure 5.5: The relationship between non-limiting water range (NLWR) and relative bulk density (RBD) for ten forestry soils compacted at water contents corresponding to a matric potential of - 33 kPa.

For most soils there is a gradual decrease in NLWR with increasing RBD initially and then a rapid tapering off in NLWR. For all the soils selected here this rapid decrease in NLWR takes place between 0.8 and 0.9 RBD. Soils with the highest initial NLWR, i.e., the Lusiki loam (Lm-h, 3A) and the Inanda sandy clay loam (SaClLm-h, 5A), also have the most rapid decrease in NLWR with increasing RBD. For all the soils shown in Figure 5.5 the zero NLWR is reached between 0.88 and 0.98 RBD. For each soil, the rapid decrease in NLWR corresponds to the RBD, at which penetration resistance and aeration become limiting with increasing compaction. This was illustrated by the narrowing of the compaction envelopes in Figure 5.3 (a - h) as these two parameters become limiting with increasing bulk density. An important feature of Figure 5.5 is that NLWR reaches very low levels, and in most cases is zero, at an RBD of 0.95. This occurs regardless of the maximum bulk density (MBD) of a particular soil. In other words, two soils with widely varying MBDs, for example the Kranskop silty clay (6A, MBD = 1.32 Mg m^{-3}) and the Hutton sandy loam (14A, MBD = 1.89 Mg m^{-3}), have a very similar physical quality as depicted by the NLWR despite very large differences in classically expressed "compactibility", i.e. MBD.

Results presented in Figure 5.5 also show that for two soils, the Cartref sandy loam (SaLm-h, 2A), and the Kranskop clay (Cl, 19A), NLWR becomes larger with increasing RBD up to a point and then becomes less again. This demonstrates the beneficial effect of compaction on the AWC of certain soils (Archer and Smith, 1972; Agrawal *et al.,* 1987). Care must be taken when choosing units to express changes in either NLWR or AWC in soils with bulk densities less than 1.0 Mg m^{-3}, such as humic silty clays and clays. With increasing RBD, soils which will show a decrease in NLWR, when expressed on a mass basis, may show an increase in NLWR up to a point before declining again when expressed on a volumetric basis. This is the case for the Kranskop clay (Cl, 19A in Figure 5.5) due to the volumetric water content being lower than the mass water content at the same bulk density when bulk densities are less than 1.0 Mg m^{-3}.

5.3.2.5 The effect of compactive effort on the NLWR

The previous section presented a useful representation of the effect of compaction on the NLWR by considering changes with respect to RBD. It should be emphasised, however, that because of the different compression characteristics of soils there is no inference on how easily the NLWR will change with compactive effort. The effect of compactive effort on the NLWR, as demonstrated by the compaction envelopes earlier in this chapter, is summarised more clearly in Figure 5.6. This shows the effect of compactive effort, expressed as a range of externally applied pressures, on the changes in the NLWR (mm m^{-1}) for ten textural classes when compacted at water contents corresponding to a matric potential of -33 kPa for each textural class. The matric potential of -33 kPa was chosen as it approximates the critical water content of maximum compressibility and compactibility determined in Chapter 3. The water content at this matric potential was determined for all the soils in this study so it could be clearly defined on the compaction envelopes. For reference, the relationship between -33 kPa and water content and bulk density is given in the compaction envelope for each soil in Figure 5.3 (a - h).

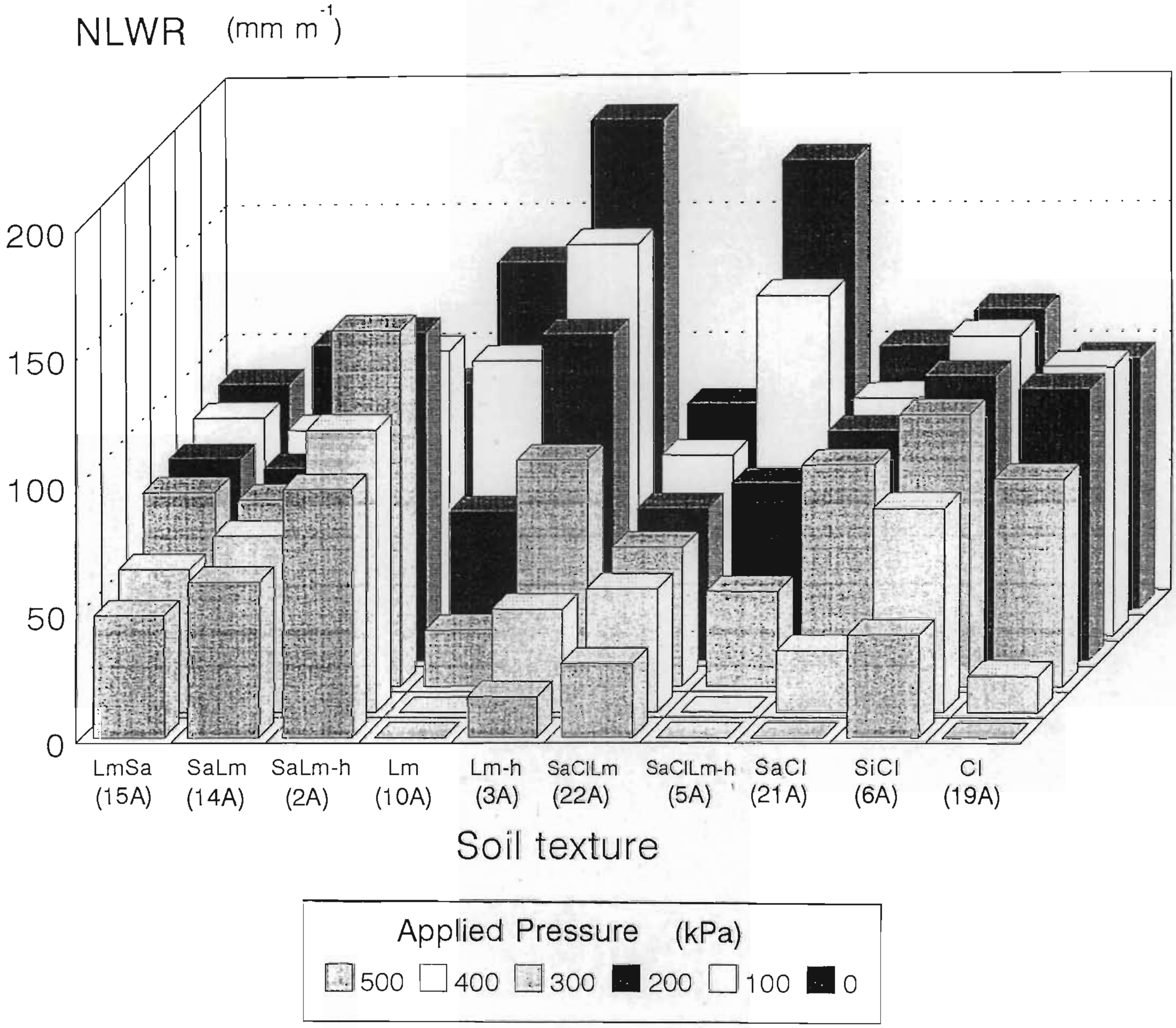


Figure 5.6: The relationship between non-limiting water range (NLWR) and applied pressures for ten forestry soils compacted at water contents corresponding to a matric potential of - 33 kPa.

Figure 5.6 shows that decreases in the NLWR are not constant for an increment of applied pressure. For the Kranskop sandy clay (SaCl, 21A), Kranskop silty clay (SiCl, 6A) and Kranskop clay (Cl, 19A) soils, for example, the maximum rate of decrease in NLWR occurs between applied pressure of about 300 and 500 kPa. This is important information for it demonstrates that below 300 kPa relatively little change in the NLWR occurs. Above these pressures the NLWR decreases more rapidly for an increment of applied pressure. The reason for this rapid tail off in the NLWR for these clayey soils is that in general, critical penetration resistances are encountered sooner at higher compaction levels than for soils with lower clay contents (*viz,* Figure 4.2, p 100). For low ground pressures little decrease in soil physical quality can be expected but above a certain threshold of compactive effort the decrease in physical quality is pronounced.

Figure 5.6 shows that with increasing applied pressure the NLWR falls quite rapidly for the Cartref loam (Lm, 10A), Inanda sandy clay loam (SaClLm-h, 5A) and Lusiki loam (Lm-h, 3A). This occurs despite all of these soils possessing very high NLWRs in the uncompacted state. For these soils the rapid decline in NLWR can be attributed to the decrease in FC on both a mass and volumetric basis (Figure 5.3b, c and d) with increasing compaction. The narrowing of the NLWR for the Inanda sandy clay loam soil was accentuated by the lower limit of the NLWR being determined by critical penetration resistance at relatively low levels of applied pressure (Figure 5.3d). The rapid change in NLWR for only moderate increases in applied pressure shows that these soils are quite susceptible to changes in soil physical quality following compaction, despite two of them being classified as humic topsoils. Even though large changes in NLWR occur with increasing compactive effort the Lusiki loam soil still enjoys a NLWR of 88 mm m^{-1} after 400 kPa has been applied (but only 38% of the initial NLWR). Thus, large initial NLWR values act to some extent as a buffer against excessive compaction but do not affect the rate of change. This could be an important consideration when defining excessive compaction and will be addressed later.

The Hutton sandy clay loam soil with a low organic carbon content (SaClLm, 22A, Figure 5.5) has a low AWC and is highly compressible (C_{max} = 0.503, Chapter 3, Table 3.2). However, Figure 5.5 shows that although initial NLWR is very low at 80 mm m^{-1} the relative change in NLWR with increasing applied pressure is small up to an applied pressure of 400 kPa. Inspection of the compaction envelope in Figure 5.3e reveals the reason for this. The initial NLWR is low due to the proximity of water contents at -10 kPa and wilting point. As the bulk density increases quite rapidly with increasing applied pressure, i.e. high compression index, the NLWR continues to be determined by these two parameters which do not change substantially even at relatively high bulk densities. Critical aeration and penetration limits are not encountered until an applied pressure of 600 kPa is maintained, which is considerably more than for the Kranskop clay, Kranskop sandy clay loam and Lusiki loam mentioned previously. Thus it can be concluded that for the Hutton sandy clay loam soil the interrelationships of the critical growth parameters and compaction level are more important determinants of changes in soil physical quality than compression index alone.

An interesting case is the Cartref loam soil which has a high initial NLWR (140 mm m^{-1}) and which declines very rapidly to zero with increasing applied pressure (Figure 5.6). The reason for this is a combination of moderate compression index (C_{max} = 0.397, Chapter 3, Table 3.2) and low aeration porosity at high matric potentials. The latter determines the upper limit of the NLWR from very low compaction levels (see Figure 5.3b). As mentioned previously, this soil is also unstable, prone to slumping in the field and has signs of waterlogging even in the topsoil.

Figure 5.6 shows that little change in NLWR occurs with increasing compactive effort for the Fernwood loamy sand and Hutton sandy loam (LmSa and SaLm respectively). This can be explained almost entirely by the low compression indices of these soils (0.145 and 0.248) which means that there is very little change in bulk density for an increment of applied pressure. Hence, the NLWR of both of these soils taper off quickly with increasing RBD (Figure 5.5) but not with increasing compactive effort (Figure 5.6).

5.3.2.6 A comparison between NLWR and available water capacity (AWC)

For all the soils in this study NLWR was the same as AWC at low relative bulk densities and then deviated from AWC substantially at a critical compaction level (Figure 5.7). As explained previously, this was due to the increasing likelihood of critical penetrometer soil strength and aeration porosity becoming limiting for root growth at higher and lower water contents than wilting point and FC respectively. An example of this behaviour is illustrated in Figure 5.7 for four different soils, and indicates clearly that soils which maintain a large traditional AWC even at high levels of soil compaction can still have very low values of NLWR. These results are similar to those of Topp *et al.* (1994) who found that the NLWR at field bulk density was nearly always less than the traditional AWC. This was mainly due to critical penetration resistances being encountered even at low levels of compaction and usually before critical aeration levels were encountered. In one case Topp *et al.* (1994) reported zero NLWR in two clay loam horizons in their study despite an AWC of 66.3 and 43.9 mm m^{-1} for the topsoil and subsoil respectively. The results presented in this chapter suggest that although the compaction level at which critical penetration resistance varies with soil texture, this compaction level is normally much higher than field bulk density (see compaction envelopes, Figure 5.3 (a - h)). It was shown in Chapter 4 that penetration resistance at wilting point only exceeded critical values, i.e. 2 MPa, for soils with over 30% clay at moderate to high relative bulk densities, that is, at RBDs of over 0.8. The results reported here indicate that it is unrealistic to use AWC values for highly compacted soils or soils in poor structural condition.

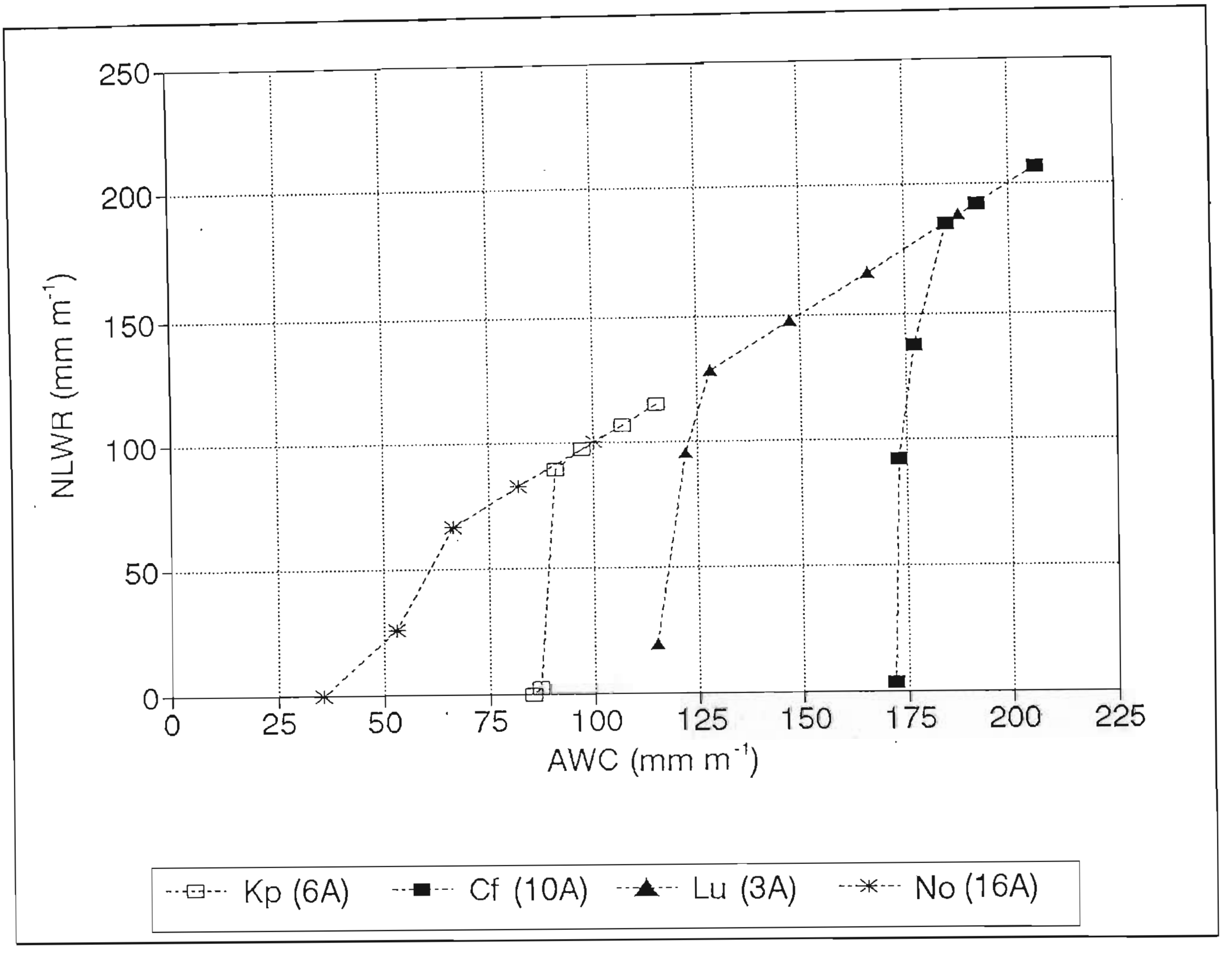


Figure 5.7: The relationship between NLWR and available water capacity (AWC) for four selected forestry soils.

5.4 DISCUSSION AND CONCLUSIONS

Establishing the NLWR for a soil depends on an adequate definition of its upper and lower limits. These limits are usually defined by commonly accepted growth limiting factors such as field capacity (FC), wilting point, critical penetration resistance (CPR) and critical aeration porosity (Letey, 1985). In general, for the soils studied here, the upper limit was found to be defined by field capacity (FC) at low levels of compaction and by critical aeration porosity at higher compaction levels. Furthermore, wilting point defined the lower limit of the NLWR at lower bulk densities and CPR at higher bulk densities. The importance of each parameter at a particular level of compaction in defining the upper and lower limit of the NLWR varied depending on soil type.

Since soil properties that affect CPR were established for a range of forestry soils (Chapter 4), and as critical aeration porosity was determined by its simple mathematical relationship with bulk density and water content, factors which influenced FC and wilting point as critical parameters of the NLWR were examined. The information presented in this chapter showed that the relationship between FC and bulk density depended upon two factors: i) soil type, and ii) the designated matric potential. In general, FC increased with increasing compaction when water content was expressed on a volumetric basis. The effects of increasing bulk density on FC when water content was expressed on a mass basis were more complex and no clear patterns emerged. A problem with interpreting the effects of compaction on FC is that the WRCs for various bulk densities of the same soil "crossed" between matric potentials of -1.0 and -11.0 kPa which is the most common range for the designation of FC (Smith and Thomasson, 1974; Cassel and Nielson, 1986). There is little doubt that the creation of meso- and micro-pores at the expense of macropores accompanies reduction in porosity during the compaction process (Hill and Sumner, 1967). However, the absolute change in pore size distribution and its relevance to the resultant water retentivity curve (WRC) are undoubtedly complicated and reflect complex changes in pore geometry following soil compaction.

In all cases in this study compaction resulted in the "flattening" of the S-shaped WRC expressed on either a mass or volumetric basis. This had the implicit effect of lowering the water release index, or gradient of the semi-log plot of water content against matric potential. It is not clear, however, what significance these changes are likely to have for root and plant growth as there was no clear relationship between water release index and AWC.

As the WRC was not determined for each soil at a wide range of bulk densities, the effects of compaction on the available water capacity (AWC) could not be ascertained precisely, but it is believed that a very useful insight was obtained. When expressed on a volumetric basis, AWC generally decreased following soil compaction. An increase in AWC was noted following compaction of some soils in the study but a decrease in AWC resulting from even higher levels of compaction then ensued. Increases in FC following compaction did not necessarily result in increases in AWC as suggested by Reeve *et al.* (1973) as wilting point also increased with compaction. The effect of compaction on AWC expressed on a mass basis was more complicated because, although compaction had little effect on wilting point, the effect of compaction on FC was complex. For a range of bulk densities, WRCs "crossed" when expressed on mass basis at matric potentials of between -2.0 kPa and -1500 kPa depending on soil type.

When considering the effects of compaction on water retention, the expression of water content on a volumetric or mass basis is more than just semantics. While differing expressions do not necessarily imply any physical differences in water - energy relations for a particular soil, they do convey different types of information related to pore geometry and available water capacity. For example, the flattening of the WRC during compaction is the result of a loss in total porosity and a modification in pore size. The actual change in pore geometry is better reflected by the expression of the water content on a mass basis without consideration of volume effects. From a practical point of view, changes in available water are better expressed on a volumetric basis.

By superimposing critical values of soil physical properties defining excessive compaction on water-pressure-density (W-P-D) diagrams developed in Chapter 2, "compaction envelopes" provided a rational framework for determining the outcome of a particular level of wheeled traffic on soil properties which may affect root and shoot growth. These diagrams also allowed an assessment of the relative compaction risk of a range of soils and the effect that changes in critical growth limiting parameters may have on that compaction risk evaluation. Soils with a high number of iso-stress lines within the compaction envelope bounded by the upper and lower limits of the NLWR showed resistance to excessive compaction whereas those with few iso-stress lines were more susceptible to compaction. As the CPR line occurred in the upper portion of the compaction envelope increases, in CPR would not result in an important change in the NLWR for most soils. The exception to this was for soils with high clay and organic carbon contents. A lowering of CPR to 1 MPa, for example, would have a major effect on the NLWR, resulting in CPR being the dominant lower limit of the NLWR. It was demonstrated that increases in critical aeration porosity, for example increasing to 15%, would have a substantial effect on the NLWR of soils which have compaction envelopes in close proximity to critical aeration porosity.

The designated matric potential for FC would have a considerable effect on the NLWR and therefore compaction evaluation, the relative importance of these changes depending on soil type. The higher the matric potential used for field capacity the more likely that aeration problems will be associated with increasing compaction. It is of interest to note that a lower threshold of aeration porosity (i.e greater than 10% used in this study) would render changes in the designated matric potential for FC even more important. The compaction envelopes have shown that, in contrast to the sensitivity of the NLWR to the selected matric potential for FC, changes in the designated wilting point would have to be fairly substantial to have a large effect on the lower limit of the NLWR and are therefore not considered to be important here.

The dynamics presented in this chapter enabled an evaluation of the relationship between compressibility or compactibility and change in soil physical quality as expressed by the NLWR with compactive effort. It is clear from the data presented in this chapter that compactibility expressed by maximum bulk density has no relationship to changes in critical growth parameters which are affected by compaction. Most soils in this study attained NLWR values of zero between relative bulk densities of between 0.88 and 0.98, regardless of the soils' maximum bulk density. It can be concluded that factors which are important in evaluating the packing density of soils (Gupta and Larson, 1979; Van Huyssteen, 1989) give meagre information regarding the likely changes in the soil as a rooting medium following compaction. Though the relationship between RBD and NLWR gives no information concerning the ease with which a soil will attain a particular NLWR, from a practical standpoint, the relationships are useful inasmuch as very high RBDs represent a condition in forestry soils caused by continuous trafficking. Such situations commonly exist where harvesting extraction operations take place on the same extraction trails at the end of each rotation.

Compressibility refers to the ease with which a soil will decrease in volume at a given water content for an increment of applied stress, and as such is an index of compaction susceptibility. No simple correlation exists between compressibility and the ease with which a soil will suffer from excessive compaction as defined by critical NLWR values. Soils which are highly compressible undoubtedly reach limits defining excessive compaction more rapidly, but even relatively incompressible soils will become excessively compacted if their initial NLWR is low. The point that needs to be made here is that soils possessing initially low NLWR values, regardless of their compressibility, are extremely susceptible to excessive compaction. In this respect the limits which define excessive compaction become very important in any compaction risk assessment and may vary with crop tolerances.

It was also clear from this study that if factors such as penetration resistance are high enough to affect root growth and are therefore incorporated into an index of soil physical quality, such as the NLWR, then compaction risk must also take soil consistence into account, i.e. the relationship between soil strength and water content. For example, in this study the Kranskop silty clay and

Kranskop clay (with high organic carbon contents) had low to moderate compressibilities but their NLWRs were bounded at relatively low bulk densities by critical penetration resistances (Figure 5.3g and h). The opposite was the case the for the Hutton sandy clay loam and Kranskop sandy clay (Figure 5.3e and f) which were highly compressible but showed little evidence of critical penetration resistance affecting the NLWRs meaningfully.

As the changes in NLWR with increasing compactive effort are not linear, increasing in some cases and staying constant followed by a rapid decrease in others, it is clear that soils vary in compaction susceptibility depending upon the relative intensity of the compactive effort. If a low intensity traffic regime is adopted the compaction risk for a group of forestry soils should be assessed differently to a situation where a traffic regime of moderate intensity is enforced. However, high intensity traffic regimes will invariably result in high RBDs and excessive compaction, all soils being equally at risk. Even a soil having a low compressibility and a low maximum bulk density will not prevent a large deterioration in soil physical quality as expressed by the NLWR. By considering the effects of RBD and applied pressure on NLWR this study has shown that all soils are susceptible to excessive compaction with a sufficiently high compactive effort corresponding to intensive traffic regimes. Establishing a credible index of compaction for forestry soils will ultimately depend on the type of management operation employed.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

Management of compaction in a forestry setting demands information on a very wide range of soils which represent the broad range of geological and climatic zones encountered in the major commercial timber growing regions of South Africa. Van der Watt (1969) stated that there are two possible approaches to establish generally applicable principles for the great variety of naturally occurring soils. Firstly, and the one that has been most frequently adapted by the majority of researchers in South Africa, is the method of selecting a group of soils related by their chemical or physical composition and the deduction of quantitative inter-relationships between properties. The other method, which was the one employed here, is to analyse data from a large number of dissimilar soils which may result in a logical grouping of soils with fairly accurate specific property interrelationships.

The principal objective of this research was the identification of forestry soils likely to be at most risk from excessive compaction. It was anticipated that this would allow the development of a framework for the routine prediction of compaction risk and susceptibility of South African forestry soils. It was realised at the outset that, in the absence of threshold variables which define excessive compaction, such an assignment could present interpretational problems. The approach adopted in this thesis was to establish principal facets and indices of compaction behaviour of forestry soils and then relate these to changes in the soil physical condition resulting from compaction. By evaluating the changes in soil physical quality due to compaction allows a considerable degree of flexibility in the interpretation of a compaction risk assessment when new research results are forthcoming regarding critical root and plant growth parameters, seasonal soil water balance of forestry soils and seasonal root growth behaviour of forest species. Thus the compaction risk assessment emanating from results of this study should be regarded as dynamic rather than static.

6.1. Compaction behaviour of forestry soils

In order to gain an understanding of compaction behaviour an objective of this work was to provide a quantitative description of forestry soil behaviour under conditions of varying compactive stresses and water contents. The model which was found to be the most suitable for expressing the relationship between bulk density and applied pressure and water content was similar to those presented by Amir *et al.* (1976), Larson *et al.* (1980) and O'Sullivan, (1992), and was given in Equation 2.5.

The model is essentially empirical in nature as it was developed from the relationship between bulk density and applied pressure for a range of water contents on disturbed samples. However, because a wide range in soils were used to derive the relationship it allowed an important insight into the compaction behaviour of very different forestry soils. In their review on future research needs in soil compaction, Schafer *et al.* (1992), criticised such models explaining that the model inadequately describes the compaction process below principal applied pressures of 100 kPa. A practical point of this argument is that agriculturalists also need to define compaction behaviour of freshly tilled soil. A soil in a loosened state is most compressible (Van Huyssteen, 1989) and even relatively small applied pressures may result in compaction. As soils in timber plantations have not been loosened prior to harvesting operations, it is doubtful whether such a criticism is relevant in a forestry context where one of the principal concerns is the high axle load during timber extraction operations.

The primary value of the model developed here was to provide a better understanding of the differences in compaction behaviour between soils of varying composition. In this respect the model, although empirical in nature, enabled an evaluation of the relative importance of water content and applied pressure in affecting the compaction behaviour of the soils studied. Furthermore, regression equations developed between constants in the model and soil physical properties allowed an insight into which soil physical properties were related to the various facets of compaction behaviour. It is believed that this information is of immense practical value. For example, water content had the largest effect on the compaction process for soils with between 45 and 65% clay plus silt content and was least important in affecting compaction behaviour for soils with high organic carbon contents and high sand (low clay) contents. Most South African timber plantations occur in regions with strongly seasonal rainfall and this type of information will allow, on a practical level, prioritisation of harvesting operations to certain soil types depending on soil water conditions.

To the extent that local geology is a principal determinant of particle size distribution and may also affect organic carbon content, it is a very useful indicator of compaction behaviour. Broadly speaking, soils which were derived from granite were highly compressible and their compaction behaviour, together with soils derived from sandstone, was highly dependent upon water content at the time of compaction. This contrasted with soils derived from base-rich parent materials, such as dolerite and diabase, which were slightly to moderately compressible and where water content influenced compaction behaviour to a much lesser extent.

6.2 Soil properties related to compressibility and compactibility

Having established the basic compaction behaviour of forestry soils, it was necessary to examine relationships between soil properties and indices of compaction susceptibility. In this respect two traditional measures of compaction susceptibility were used: maximum bulk density (MBD) which defines compactibility, and compressibility as measured by the compression index, *C*. Relationships were then established between these measures and a range of soil chemical and soil physical properties resulting in a first approximation of compaction risk in terms of both MBD and *C* simultaneously. It is believed that this is a unique approach for such a wide range of soils. A number of studies have regarded compaction susceptibility exclusively in terms of either MBD (Alexander, 1980; Van der Watt, 1969; Moolman, 1981; Van Huyssteen, 1989) or compressibility (Larson *et al.,* 1980; Saini *et al.,* 1984).

It was clear from the work on compaction behaviour that *C*, which is essentially the slope of the straight line portion of a plot of bulk density against the log of applied pressure, varied depending upon water content. An important finding was that analogous to compaction behaviour under the conditions of the Proctor technique (Proctor, 1933) for MBD determination, *C* determined under the conditions of a uniaxial applied pressure also had a maximum value and that it was possible to define the water content at which this value occurred. Usually this water content corresponded to matric potentials of between -33 kPa and -100 kPa. Thus maximum C or C_{max} was preferred to C as it refers to maximum compressibility of a soil rather than the average compressibility, the property used in Equation 2.5.

The large range of MBD values, from 1.24 to 2.00 Mg m^{-3}, reported in this study reflected the wide range of particle size distributions and organic matter contents of the soils investigated. Compared to previous studies in South Africa (e.g. Van der Watt, 1969; Moolman, 1981) the mean compactibility value was relatively low. However, even lower values of MBD were reported by Northey (1966) due to the formation of many of the soils from recent volcanic material in New Zealand.

In terms of the regression equations which were developed between soil physical properties and indices of compactibility and compressibility, the following conclusions were forthcoming:

1. Very good correlations were achieved between measures of particle size distribution, particularly clay plus silt rather than clay content, and both compactibility and compressibility.

2. Both compactibility and compressibility were significantly correlated to organic carbon content as measured by loss-on-ignition (Donkin, 1991). As poorer relationships were reported between indices of compaction and Walkley-Black organic carbon it is suggested that LOI organic carbon reflects a textural component in addition to organic matter.

3. Indices of compaction susceptibility were influenced more by particle size distribution than organic carbon content. Clear effects of organic carbon on compaction behaviour were only evident for soils with low clay contents (<25%).

4. No clear relationship between compactibility and compressibility was found. Compactibility generally increased with decreasing clay plus silt content whereas compressibility increased up to about 70% clay plus silt before decreasing again.

5. Compressibility as measured by C_{max} was well predicted for all the soil orders in this study by the models of Gupta and Allmaras (1987). The contention of Larson *et al.*

(1980) that compression index increases up to 33% clay before levelling off is not supported by the data in this study and a higher clay content "threshold" is indicated.

6. C_{mod}, the compression index used in the compaction behaviour model of Chapter 2, was generally overpredicted by the Gupta model and it is believed that this is due to the wider range of water contents present in the soils during compression testing compared to the Gupta data.

7. When detailed local soils information is lacking, geology, even at a scale of 1:250 000 is a useful surrogate for a first approximation of compaction risk assessment for South African forestry soils.

An important conclusion from this study is that it is difficult to define compaction susceptibility solely in terms of indices of compactibility or compressibility particularly as there is no clear relationship between these two properties. In South Africa, soils which are considered most susceptible to compaction have traditionally been assumed to be those with highest maximum bulk densities (Van der Watt, 1969; Moolman, 1981; Van Huyssteen, 1989). However, Gupta and Allmaras (1987) suggested the ease or susceptibility of soils to compact implies the rate at which the soil compresses for an increment of applied load at a given water content. Furthermore, Gupta and Allmaras (1987) contended that even this measure does not give adequate information regarding the effects that these changes have on the soil-water-air matrix with respect to root and plant growth.

6.3 Excessive compaction of forestry soils

6.3.1 Effect of compaction on mechanical resistance as measured by penetrometer soil strength (PSS)

Penetrometer soil strength (PSS) is a measure often used as an index of soil compaction. As this property changes considerably during the year with wetting and drying cycles (Spain *et al.*, 1990) an objective of this work was to characterise the effect of soil compaction on the relationship between PSS and water content. An additional aim was to determine the extent to which these changes were influenced by soil properties. The main conclusions of this study are:

1. Bulk density has a considerable effect on the relationship between PSS and water content. PSS increases more sharply with increasing bulk density as water content decreases.

2. The relationship between PSS, bulk density and water content is strongly influenced by soil properties, particularly clay content. For cohesive soils (generally those soils with over 20% silt plus clay) increasing clay content reduces the *rate* at which PSS increases with decreasing water content at any compaction level. Nevertheless, an increase in clay content increases PSS at wilting point for moderate and high levels of compaction. The inference here is that the likelihood of PSS becoming limiting for root growth before wilting point is reached is greater the more clayey the soil. Thus, although a very rapid rise in PSS occurred for the so-called "hardsetting soils" (Mullins *et al.*, 1989) as the soils dried, critical penetration resistances were usually attained at just before or about wilting point for these soils.

3. Similar to clayey soils, non-cohesive soils (< 20% silt plus clay) also displayed slow *rates* of decrease in PSS as the soil dried although the *magnitude* of PSS was considerably less for similar matric potentials and relative bulk densities than for the finer textured soils.

4. Soils with higher clay contents generally possessed higher PSS values at field capacity. In general, it was observed that soils with less than 35% clay lost strength rapidly as the water content increased towards field capacity. However, a better relationship was obtained between organic carbon (LOI) and PSS at field capacity than with clay content, indicating that organic matter plays a role in affecting soil strength in wet soils.

5. For all the soils in the study, differences between PSS at each compaction level were least at field capacity and greatest at wilting point or drier.

6. As demonstrated by the exclusion of organic carbon from the model (Equation 4.1), it was considered that organic matter levels were generally not high enough to have a large effect on the compaction - PSS - water content relationship for most soils, although there was evidence to suggest that organic matter becomes more important

as clay content decreases. A clay content of 25% is suggested as the point below which moderate changes in organic carbon content can have an appreciable effect on PSS.

6.3.2 The effect of compaction on the non-limiting water range (NLWR)

An attempt was made to address the issue of changes in the air-soil-water matrix by measuring the effects of soil compaction on selected parameters of soil physical quality known to directly affect root growth. The approach adopted in this study was to determine the *non-limiting water range* (NLWR) for a range of soils at various compaction levels and in so doing to establish a basis for evaluating the effects of applied pressure, water content and relative bulk density on excessive compaction. In the absence of a realistic alternative this also allowed the development of a practical definition of *excessive compaction* in terms of NLWR that was alluded to by the proponents of the term, Gupta and Allmaras (1987).

The upper and lower limits of the NLWR are usually defined by commonly accepted growth limiting factors such as field capacity (FC), wilting point, critical penetration resistance (CPR) and critical aeration porosity. The assessment of NLWR requires an understanding of factors which influence the water retention characteristics of soil. In establishing the effects of compaction on the WRC for a range of soils the following conclusions were made:

1. When expressed on a volumetric basis, FC at -10 kPa increased with increasing compaction but this did not necessarily result in an increase in AWC as wilting point also increased.

2. The effect of compaction on FC is also strongly dependent on the matric potential designated for FC as the WRCs for different bulk densities for a particular soil "crossed" between -1.0 and -11.0 kPa, the lower range of which (i.e. -7.5 to -10 kPa) is commonly chosen as an approximation for FC.

3. When expressed on a mass basis, the effects of compaction on FC were complex and no clear trend was noticeable. This was attributed to the "crossover" of WRCs for different bulk densities occurring across a very wide range of matric potentials (-2.0

kPa to -1500 kPa).

4. Compaction resulted in a decrease in total porosity and an increase in the number of mesopores at the expense of macropores. The relative balance between these two processes was dependent on soil type and was reflected by the effects of compaction on readily available water (RAW) and AWC.

5. Water retention increased at wilting point with increasing compaction, the magnitude of which was dependent upon whether water content was expressed volumetrically or on a mass basis. Interestingly, and in contrast to the work by Hill and Sumner (1967), no large increase in the number of small pores was achieved by compaction, even for the clayey soils.

6. Compaction commonly resulted in a flattening of the characteristic S-shape of the WRC and this was reflected in the consistent reduction in the water release index for each soil with increasing bulk density.

7. The effect of compaction on AWC (water content between -10 kPa and -1500 kPa) varied depending upon soil type but in general the effect was to reduce AWC. In some cases compaction increased AWC up to a point after which it declined.

Superimposing critical soil physical parameters for root and plant growth on the WPD diagrams developed in Chapter 2 allowed an assessment of the relative compaction risk of a range of soils and the effect that changes in critical growth limiting parameters may have on assessing compaction susceptibility. The resultant diagrams were termed "compaction envelopes". These allowed determination of the NLWR and also the identification of applied pressures and water contents not conducive to excessive compaction of forestry soils.

The compaction envelopes showed that the upper limit (wet end) of the NLWR was controlled by field capacity at low bulk densities and aeration at high bulk densities. Choosing a higher matric potential for field capacity would make a large difference to the NLWR and would also increase the importance of critical aeration porosity at lower levels of soil compaction. Topp *et al.* (1994) noted that the 10% air-filled porosity limit was too small for adequate oxygen diffusion at depth. The compaction envelopes presented in this study show that increases in critical aeration porosity above 10% would have a major effect on NLWR and thus compaction risk evaluation, particularly if FC is at matric potentials higher than -10 kPa.

For soils with low bulk densities, wilting point determined the lower limit (dry end) of the NLWR but critical penetration resistance (CPR) became increasingly important with increasing compaction. As the WRC is relatively level or very gently sloping at very low matric potentials, changes in the designated matric potential would have very little effect on the upper limit of the NLWR. If the CPR for a particular tree species decreased then CPR would define the upper limit of the NLWR at much lower compaction levels. An important finding was that CPR defined the lower limit rather than WP at lower compaction levels for soils of higher clay content. It is interesting to note that this feature was also reported in Chapter 4 when comparing PSS values at wilting point for a range of soils.

It is believed that the compaction envelopes could assist management and fertility assessment strategies. They enable soil physical problems to be viewed holistically as it becomes possible to predict what the limiting factors are likely to be with a given change in soil structural condition. For example, soils which were known to have aeration problems (grey, massive topsoils) in the field possessed an upper limit for the NLWR close to the critical 10% air-filled porosity line. Increases in compaction of these soils simply causes the upper limit of the NLWR to be dominated by air-filled porosity. This is accentuated by the poorly drained nature of the soils which has the effect of increasing the matric potential at which the soil could be deemed at field capacity.

Relationships between relative bulk density (RBD) and NLWR were established and showed that, for most soils, NLWR decreased with increasing RBD until NLWR became zero between an RBD of 0.88 and 0.98 depending on soil type. For two soils, a sandy loam and a clay, NLWR increased up to a certain RBD and then tapered off again. A deduction that can be made from these relationships is that, regardless of soil texture and therefore maximum bulk density, soil physical quality as measured by the NLWR deteriorates in the same manner at high RBDs (usually > 0.95). Thus using MBD as a measure of compactibility assessment is unlikely to give any information as to the change in soil physical quality with increasing compaction.

Studying the effect of compactive effort on changes in NLWR was found to be an effective method of assessing the risk of excessive compaction. Changes in NLWR with increasing applied pressure are not linear and, due to the numerous interactions involved, tend to be complex. Because of this it is clear that soils vary in their susceptibility to compaction depending upon the relative intensity of compaction as well as the initial NLWR. Soils with a high initial NLWR value are obviously buffered to a certain extent against excessive compaction when subjected to low applied pressures. However these soils may still suffer from excessive compaction more quickly with increasing compactive effort than soils which have low initial NLWR values but which undergo only small changes in NLWR for an increment of applied pressure. The data presented in this work suggest that all soils will eventually suffer from excessive compaction with high intensity traffic regimes. Comparing soils with respect to compaction susceptibility therefore depends on the intensity of compaction and on the limits which are defined for excessive compaction. Thus compressibility affects the rate at which excessive compaction is attained but conveys no information on variation in soil physical quality (as expressed by NLWR for example) with increasing compaction.

It should also be pointed out at this stage that, although most of the soils in this study are considered to have a large degree of structural stability, soils which are dispersive or tend to slump will tend to go undergo large changes in NLWR with very little compactive effort. Although the NLWR has been utilised in this work to describe changes in soil physical quality originating from an externally applied pressure, it is proposed that the NLWR provides a useful parameter to describe the quality of unstable soils too. Constructing envelopes similar to those presented in this thesis will allow the potential limiting effects to be identified and allow the benefits of amelioration to be quantified.

6.4 Compaction risk and forestry planning

The emphasis in this study on topsoils does not presuppose that subsoils are unimportant in a forestry context. On the contrary, most commercial tree species possess rooting strategies which enable the tree to utilise the rooting volume available on some occasions to considerable depth (Stone and Kalisz, 1991). Nevertheless, most tree species maintain a considerable proportion (often above 80%) of active roots in the upper 30 cm of soil (Ruark *et al.*, 1982) and these are the regions that are changed most by compaction. Therefore, any compaction risk assessment must logically "begin at the top".

Field trials by the author and other researchers overseas have shown a complex scenario regarding the likely effects of compaction on tree growth. Trees differ from the main agronomic crops in that they possess complex and deep rooting strategies which vary temporally, spatially and from species to species. Although it is very difficult to establish with any certainty the effects of soil compaction on "long term site productivity", research conducted at the ICFR and elsewhere has indicated that only excessive compaction caused by "excessive traffic" has caused any significant short term decrease in tree growth for a range of species. The lack of response to tillage operations on regeneration (second and subsequent rotation) sites in South African timber plantations has led to suggestions that decaying root systems are providing pathways for new roots and water infiltrating to the subsoil (Nambiar and Sands, 1992). Under these circumstances the identification of "high risk" soils allows researchers to concentrate their efforts more effectively, particularly when growth responses are only pronounced when compaction is deemed excessive. In addition, the compaction risk assessment emanating from the data presented in this thesis permits a rational appraisal of soils which present the greatest risk of deleterious changes taking place, and where utmost caution should be exercised by the harvesting forester.

6.5 Implications for soil classification in South Africa

The work and relationships presented in this thesis have shown that a number of limitations are evident in the South African classification system when considering practical interpretations from the point of view of compaction risk assessment and the soil physical properties resulting from compaction.

This thesis provides evidence that soil texture, and to a lesser extent organic carbon, are the principal factors affecting the behaviour of forestry soils in response to compaction. The formal omission of the textural classes which formed the basis of soil series in the first edition of the classification (Macvicar *et al.*, 1977) is not supported even though the Soil Classification Working Group (1991) maintain, in the 2nd edition that "*soil texture is not used as a differentiating criterion, but will be used regularly in conjunction with forms and families*".

If it is not to be used as a differentiating criterion, why use it at all? If soil texture criteria are reintroduced at any level then the arbitrary clay content limits of Macvicar *et al.* (1977) should be replaced by clay plus silt content. From the point of view of compaction risk assessment and water retentivity properties this has considerably more merit than clay content alone or the arbitrary description of sand grade. The inclusion of silt at an appropriate level of soil classification is long overdue, particularly since the adoption of the USDA system of particle size limits. Silt contents were generally considered to be very low in South African forestry soils but the inclusion of the 0.02 to 0.05 mm fraction as silt (formerly a part of fine sand, see Appendix 5) has resulted in clay percentages frequently being equalled by silt percentages, particularly on soils developed from silica deficient parent materials such as dolerite and tillite.

While the separation of topsoils into those with low and high organic carbon levels, as represented by the orthic and humic horizons respectively, is useful, the use of 1.8% organic carbon (Walkley-Black) to separate humic from orthic topsoils remains an enigmatic distinction. The poorer correlations achieved between organic carbon (WB) and indices of compaction susceptibility have demonstrated the overriding effect of texture on physical behaviour. Compactibility, and to a lesser extent compressibility, as well as penetrometer soil strength were, however, well predicted by organic carbon as determined by loss-on-ignition. In general, better correlations were achieved between soil physical properties and LOI organic carbon than WB organic carbon. The usefulness of LOI organic carbon as a predictor of compaction and strength behaviour indicates that it may prove to be a useful classification tool in the future.

A general feature of this work was that with respect to the penetrometer soil strength - bulk density - water content relationship and the effect of compaction on the NLWR, the importance of organic carbon content increased with decreasing clay content. For soils with less than 25% clay a limit of 1.5% organic carbon (WB) would be a more appropriate criterion to separate physical behaviour of soils of similar texture. Over 25% clay the dominant factor affecting strength behaviour was clay content.

Although an in depth study was not carried out, the data presented in Chapter 5 suggested that organic matter had a considerable effect on the NLWR and AWC for soils of a similar texture, particularly for soils with less than 40% clay, thus confirming the beneficial effect of organic matter on AWC (Hudson, 1994). In this respect the present classification system worked well for loamy soils and finer but failed for sandy loams and loamy sands. The evidence presented in this thesis suggests that for soils with less than 20% clay the criterion for meaningful separation of humic and orthic topsoils should be lowered to at least 1.5% if not lower for very sandy soils.

6.6 Future research opportunities

The thrust of this thesis has been to examine factors, both external and internal, which influence the compaction process and to establish changes in physical properties of compacted soils which are related directly or indirectly to plant growth. The usefulness of measures of compaction, such as compactibility and compressibility, and the parameters which define the compacted state, such as the NLWR, ultimately depends upon a defined relationship between soil physical properties, root development and tree growth. From this point of view a number of research opportunities exist:

i) Definition of optimum states of compaction for maximum NLWR for a more extensive number of forestry soils than used in this study. In this respect a more precise definition of the relationship between water retentivity and bulk density should be sought, in particular the relationship between organic matter and water retentivity characteristics for sandy soils.

ii) A more accurate appraisal of static parameters which define the NLWR for various tree species, particularly the critical aeration porosity and critical penetration resistance for various tree species.

iii) The effect of soil compaction on spatial and temporal rooting strategies of commercial forest species. This must be carried out together with an evaluation of rooting strategies under optimum conditions.

iv) The evaluation of compaction susceptibility will be improved considerably by an adequate description of the relative importance and contribution of tree roots at different depths in the soil profile as regards water and nutrient uptake.

v) The role of previous root systems in the modification of the soil physical environment, especially with regard to water transport and rooting characteristics of tree species.

vi) The role of organic matter influencing the compaction process for soils of various textures needs to be better understood. It is recommended that these studies include techniques such as thin-section micromorphology to establish the organic:mineral interactions. Consideration of the effects of organic matter may be extended to include the role of intact root systems on the compressibility of forestry soils.

vii) Combine information on patterns of stress distribution within a soil profile with compaction response in terms of NLWR.

It should be pointed out that some of these topics are the subject of current research programmes at the ICFR.

In a recent paper on future research needs in soil compaction, Schafer *et al.* (1992) stated that despite the considerable amount of compaction research undertaken, no general practical advice is available for worldwide use on soil compaction management. The authors placed considerable emphasis on the development of better models to simulate the compaction process particularly in terms of the prediction of force systems from machinery and the propagation of these forces through the soil profile. Without wanting to underestimate the importance of this information, progress towards establishing good practical advice to the South African forestry community has not benefited from this approach in the past. A lack of information on what constitutes excessive compaction in terms of plant growth will render detailed mathematical descriptions of stress distribution of forces transmitted by wheels and tracks futile. Progress on the quantification of the compaction problem depends upon establishing "compaction cause and effect". Towards this end, the information presented in this thesis assists in the control of compaction in a forestry setting since overall vehicle load and trafficking of identifiable sensitive soils under certain water contents can to a large extent be manipulated. In this respect, a firm basis has been laid for the development of a comprehensive forestry compaction management programme.

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APPENDIX 1

Profile descriptions, site information and detailed soil physical and chemical data for each soil.

PROFILE 1

Soil:	Lu 2120
Soil Form:	Lusiki
Soil Family:	Coleraine
Soil Taxonomy:	Typic Kanhaplustalf
Location:	Crofton plantation, Highflats
Company:	SAPPI Forests
Latitude/Long:	30° 14′ 06″ S 30° 13′ 24″ E
Parent material:	Dwyka tillite
Topography:	Midslope of Undulating Upland
Altitude:	1020 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 35 :	Very dry; hard; clay loam; dark grey 10YR 4/1, slightly bleached; (when moist friable; black 10YR 2/1); weak, fine sub-angular blocky; abrupt, wavy transition to A2.
A2	35 - 45 :	Moist; loose; structureless; clay; very dark greyish brown, 10YR 3/2; (dry, pale brown, 10YR 5/3); much small gravel (< 10 mm) about 75% of horizon, some larger fragments (> 50mm), about 10% of horizon. Abrupt transition to B1.
B1	45 - 60 :	Dry; hard; clay; black, 5 YR 2.5/1; moderate, medium angular blocky; 10% saprolitic character; many fine roots on common cutans; gradual transition to B2.
B2	60 - 80 :	Moist; firm to friable; hard when dry; clay tongues (black, 5 YR 2.5/1) from above in weathering Dwyka tillite; 75% saprolite.
C	80+ :	Saprolite (weathering Dwyka tillite).

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 35	Lm	22	21	25	20	7	4	1.88	4.02
A2	35 - 45	Lm	25	24	24	14	6	8	1.68	2.22
B1	45 - 60	Cl	52	11	17	10	5	6	1.71	1.87
B2	60 - 80	Cl	47	11	24	9	4	4	1.58	1.18

PROFILE 1 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.95	5.15	0.27	2.37	2.73	0.40	1.00	6.77
A2	4.65	6.05	1.72	1.25	4.95	0.15	0.07	8.14
B1	4.90	6.40	3.18	1.10	7.18	0.08	0.12	11.66
B2	5.15	6.45	2.35	1.16	8.54	0.24	0.02	12.31

PROFILE 2

Soil:	Cf 2100
Soil Form:	Cartref
Soil Family:	Steenbras
Soil Taxonomy:	Typic Haplaquept
Location:	Crofton plantation, Highflats
Company:	SAPPI Forests
Latitude/Long:	30° 15′ 30″ S 30° 13′ 18″ E
Parent Material:	Natal group sandstone
Topography:	Midslope
Altitude:	960 m
Vegetation:	Recently planted *Acacia mearnsii*

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 40 :	Moist; friable; firm on drying; sandy loam; very dark grey, 10YR 3/1 (grey, 10YR 5/1 when dry); single grain/apedal; bleached; abrupt change to E.
E	40 - 60 :	Wet; non-sticky; sandy loam; dark greyish brown, 10YR 3/2 (light brownish grey, 10YR 6/2 when dry); single grain; frequent mottles; clear transition to lithocutanic B1.
G	60 - 75 :	Moist to wet; slightly sticky; sandy clay loam; very dark grey clay togues, 10YR 3/1; massive; frequent orange mottling; grading into TMS saprolite.
C	75+ :	Dry; hard; TMS saprolite; some soft plinthic characteristics

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 40	SaLm	13	8	9	32	34	4	0.65	1.42
E	40 - 60	SaLm	11	8	7	25	32	17	0.23	0.32
B	60 - 75	SaClLm	23	9	9	5	46	8	0.43	0.31

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.95	4.85	0.18	0.38	0.69	1.29	0.97	3.51
E	4.25	5.90	0.17	0.41	0.47	0.08	0.20	1.40

PROFILE 3

Soil:	Lu 1110
Soil Form:	Lusiki
Soil Family:	Eradale
Soil Taxonomy:	Aquic Kanhaplustalf
Location:	Crofton plantation, Highflats
Company:	SAPPI Forests
Latitude/Long:	30° 13′ 48″ S 30° 12′ 24″ E
Parent Material:	Dwyka tillite
Topography:	Midslope in gently undulating upland
Altitude:	1010 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20 :	Moist; friable (hard when dry); weakly apedal to massive; dark brown, 10YR 3/3 (grey, 10YR 5/1 when dry); slightly bleached; clear transition to B1.
B1	20 - 50 :	Moist; very firm (hard when dry); moderate, medium sub-angular blocky; few cutans; very dark grey, 10YR 3/1 (grey 10YR 5/1 when dry); clear transition to B2.
B2	50 - 70 :	Iron concretions between B1 and B2; moist; firm; weak, fine subangular blocky; matrix colours yellowish brown 10 YR 5/8; some clay tonguing into Dwyka tillite saprolite; few orange and red mottles increasing with depth.
C	70+ :	Saprolite (Dwyka tillite) with frequent orange and red mottles

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	Lm	24	17	17	25	10	7	1.66	2.37
B1	20 - 50	Lm	20	21	17	26	11	5	1.48	2.40
B2	70+	ClLm	35	16	13	24	6	6	1.13	0.72

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.85	5.05	0.10	1.06	1.58	0.07	1.23	4.04
B1	4.00	5.40	0.14	0.42	1.66	0.03	1.00	3.25
B2	4.10	6.35	0.28	0.14	1.77	0.14	0.14	2.47

PROFILE 4

Soil:	Ma 1200
Soil Form:	Magwa
Soil Family:	Connemara
Soil Taxonomy:	Ustic Kanhaplohumult
Location:	Bloemendal, near Pietermaritzburg
Company:	SAWGU/ICFR
Latitude/Long:	29° 33′ 05″ S 30° 27′ 25″ E
Parent Material:	Ecca shale
Topography:	Undulating upland plateau.
Altitude:	840 m
Vegetation:	*A mearnsii* plantation

HORIZON	**DEPTH (cm)**		**DESCRIPTION**
A1	0 - 25	:	Dry; hard; dark yellowish brown, 10YR 4/4; apedal; silty clay; clear transition to B1.
B1	20 - 60	:	Dry; hard; strong brown, 7.5 YR 4/6; apedal; clay; gradual transition to B2.
B2	60 - 80	:	Dry; hard; strong brown, 7.5R 5/6; apedal; silty clay; some fragments of weathering shale.
C	80+	:	Shale saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 25	SiCl	41	19	33	3	1	3	4.03	2.10
B1	25 - 60	Cl	60	10	27	2	1	1	3.04	2.14
B2	60 - 80	SiCl	56	10	30	3	0	1	2.32	1.03

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.95	4.75	0.04	0.89	0.56	0.05	5.23	6.77
B1	3.85	4.95	0.06	0.53	0.88	0.02	3.21	4.70
B2	3.85	4.90	0.06	0.21	0.82	0.02	3.84	4.95

PROFILE 5

Soil:	Ia 1100
Soil Form:	Inanda
Soil Family:	Himeville
Soil Taxonomy:	Ustic Kandihumult
Location:	Broadmoor Farm, Wartburg
Company:	Holley Brothers
Latitude/Long:	29° 28′ 12″ S 30° 38′ 06″ E
Parent Material:	Natal group sandstone
Topography:	Lower midslope
Altitude:	930 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20 :	Dry; slightly hard; loose when moist; sandy clay loam; apedal; many roots; dark reddish brown, 5 YR 3/2; gradual transition to B1.
B1	20 - 75 :	Dry; very hard; firm when moist; sandy clay; apedal; dark reddish-brown, 5 YR 3/3; clear, wavy transition to B2.
B2	75+ :	Dry to slightly moist; hard; clay; apedal; dark red, 2.5 YR 3/6; some sandstone fragments.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SaClLm	30	6	9	22	24	8	1.91	2.15
B1	20 - 75	SaCl	36	6	7	20	22	9	1.25	n.d
B2	75+	Cl	55	12	15	5	7	6	1.00	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.45	5.65	0.16	2.02	1.26	0.14	1.18	4.76
B1	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
B2	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

PROFILE 6

Soil:	Kp 1100
Soil Form:	Kranskop
Soil Family:	Fordoun
Soil Taxonomy:	Humic Haplustox
Location:	Woodlands plantation, Shafton, Howick.
Company:	Sappi Forests
Latitude/Long:	29° 27′ 30″ S 30° 12′ 36″ E
Parent Material:	Dolerite / Ecca shale
Topography:	Undulating upland plateau.
Altitude:	1140 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20 :	Moist; very friable; strong brown, 7.5YR 3/2; weak, fine sub-angular blocky; silty clay; clear boundary with B1.
B1	20 - 45 :	Moist; friable; strong brown, 7.5 YR 4/6; well micro-aggregated, apedal; clay; wavy, diffuse transition to B2.
B2	45+ :	Moist; very firm; dark red, 10R 3/6; moderate, fine sub-angular blocky; clay; few cutans; fragments of weathering dolerite.

(Pit dug to 120 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SiCl	51	17	28	2	1	2	5.42	5.77
B1	20 - 45	Cl	46	10	19	10	2	13	3.57	2.64
B2	45+	Cl	64	12	11	3	5	4	2.14	1.09

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.45	5.65	0.16	2.02	1.26	0.14	1.18	3.55
B1	4.75	5.95	0.20	0.80	0.96	0.19	0.11	3.26
B2	5.15	5.85	0.13	0.85	0.55	0.08	0.03	1.64

PROFILE 7

Soil: Kp 1100
Soil Form: Kranskop
Soil Family: Fordoun
Soil Taxonomy: Humic Haplustox
Location: Woodlands plantation, Shafton, Howick
Company: Sappi Forests
Latitude/Long: 29° 27′ 06″ S   30° 13′ 48″ E
Parent Material: Dolerite
Topography: Upper midslope in undulating upland plateau
Altitude: 1210 m
Vegetation: *E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 25 :	Dry; loose; strong brown, 7.5YR 3/2; weak, fine sub-angular blocky; clay; clear to abrupt transition to B1.
B1	25 - 60 :	Dry; slightly hard; brown, 7.5 YR 4/4; apedal; clay; wavy, diffuse transition to B2.
B2	60+ :	Moist; firm; dusky red, 10R 3/4; apedal to weak, fine sub-angular blocky; clay.

(Pit dug to 120 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 25	Cl	56	9	12	11	8	4	3.21	2.64
B1	25 - 60	Cl	52	10	14	13	7	4	3.08	2.31
B2	60+	Cl	56	9	10	16	7	2	2.66	1.21

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.20	4.50	0.14	0.49	0.78	0.20	1.95	3.56
B1	4.45	5.45	0.16	0.42	0.94	0.13	0.49	2.14
B2	4.80	5.85	0.14	0.38	0.46	0.09	0.08	1.15

PROFILE 8

Soil:	Ia 1200
Soil Form:	Inanda
Soil Family:	Highlands
Soil Taxonomy:	Typic Kanhaplustult
Location:	Ukalinga, Pietermaritzburg
Company:	University of Natal (experimental farm)
Latitude/Long:	29° 40′ 12″ S 30° 24′ 12″ E
Parent Material:	Shale Colluvium
Topography:	Crest, level upland plateau
Altitude:	840 m
Vegetation:	*Themeda hyparrhenia* grassland

HORIZON	DEPTH (cm)		DESCRIPTION
A1	0 - 35	:	Dry; hard; brown, 10 YR 3/4 (dry), 10 YR 3/3 (moist); clay; moderate, fine sub-angular blocky; clear, slightly wavy transition to B1.
B1	35 - 65	:	Dry; hard; dark reddish-brown, 5 YR 3/4 (dry), 5 YR 3/3 (moist); clay; apedal; few iron concretions.
B2	65 - 100	:	Dry; very hard; apedal; clay; numerous iron concretions and gravel; dusky red, 2.5 YR 3/4; some weathering shale and small shale fragments; weak, fine sub-angular blocky; clay skins on gravel and concretions.
C	100+	:	Weathering Shale

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 35	SiClLm	40	16	29	6	3	7	2.36	3.58
B1	35 - 65	Cl	50	14	23	2	1	10	1.27	1.06
B2	65 - 100	Cl	59	9	13	2	1	16	1.39	0.710

PROFILE 8 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.55	5.50	0.17	5.41	3.30	0.18	0.60	9.66
B1	4.95	6.10	0.62	4.51	4.76	0.18	0.20	10.27
B2	5.15	6.40	0.92	4.99	6.23	0.51	0.20	12.85

PROFILE 9

Soil:	No 2200
Soil Form:	Nomanci
Soil Family:	Peakvale
Soil Taxonomy:	Pachic Haplumbrept
Location:	Ifafa, southern Natal
Company:	MONDI Forests
Latitude/Long:	30° 26′ 12″ S 30° 36′ 48″ E
Parent Material:	Pellitic gneiss/schist
Topography:	Midslope
Altitude:	140 m
Vegetation:	5 year old *E. grandis* plantation (ex sugar cane lands)

HORIZON	DEPTH (cm)		DESCRIPTION
A1	0 - 60	:	Wet; very sticky; massive; sandy clay loam; very dark greyish brown, 10YR 3/2; gradual transition to B1.
B1	60+	:	Wet; slightly sticky; clay; moderate, subangular blocky; tonguing into schist, gneissose saprolite; dark brown, 10YR 3/3.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 60	SaClLm	27	8	14	20	15	16	0.61	0.95
B1	60+	Cl	50	10	14	15	5	6	n.d.	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.80	4.30	0.19	0.69	0.37	0.39	1.37	3.01
B1	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

PROFILE 10

Soil:	Cf 2200
Soil Form:	Cartref
Soil Family:	Witzenberg
Soil Taxonomy:	Typic Haplaquept
Location:	Saiccor plantation, Umkomaas
Company:	SAPPI Forests
Latitude/Long:	30° 12′ 42″ S 30° 46′ 36″ E
Parent Material:	Dwyka tillite
Topography:	Midslope
Altitude:	110 m
Vegetation:	Newly planted *E. grandis* plantation (ex sugar cane lands)

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 30 :	Moist; loose; very hard when dry; massive; loam; mottles in root channels; very dark greyish brown, 10YR 3/2 (light brownish grey, 10YR 6/2 when dry); slightly bleached; abrupt change to E.
E	30 - 50 :	Very dry; very hard; massive, hardsetting; loam; frequent orange mottles; greyish brown, 10YR 5/2 (dark greyish brown, 10YR 4/2 when moist); clear transition to B1.
B	50+ :	Wet; slightly sticky; medium moderate, subangular blocky; tongiung into massive Dwyka saprolite; common gravel; dark greyish brown, 10YR 4/2; frequent orange mottling.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	Lm	16	18	16	34	13	3	0.61	0.95
E	30 - 50	Lm	19	6	14	38	16	6	0.50	0.59
B1	50+	Lm	22	14	16	28	12	8	0.64	0.61

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.80	4.30	0.19	0.69	0.37	0.39	1.37	3.01
B1	3.85	5.95	0.17	1.07	0.71	0.38	3.43	5.76
B2	4.75	6.65	0.41	1.89	3.36	0.72	6.47	12.85

PROFILE 11

Soil:	Fw 1210
Soil Form:	Fernwood
Soil Family:	Hopefield
Soil Taxonomy:	Typic Ustipsamment
Location:	Flatcrown, Kwambonambi, Zululand
Company:	Mondi Forests
Latitude/Long:	28° 30′ 24″ S 32° 10′ 18″ E
Parent Material:	Recent quaternary sands
Topography:	Level plain
Altitude:	30 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 30 :	Moist; loamy sand; loose; yellowish brown, 10YR 5/4; single grain; gradual transition to E.
E	30+ :	Moist; loamy sand; loose to friable; single-grain; light yellowish brown, 10YR 6/4; becoming slightly paler with depth.

(Pit dug to 120 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	LmSa	9	3	2	41	39	6	0.20	0.29
E	30+	LmSa	8	3	5	40	35	9	0.05	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.45	5.80	0.06	0.48	0.20	0.01	0.08	0.83
E	4.10	6.60	0.02	0.35	0.06	0.02	0.04	0.59

PROFILE 12

Soil:	Fw 1220
Soil Form:	Fernwood
Soil Family:	Duinzicht
Soil Taxonomy:	Alfic Ustipsamment
Location:	Salpine, Kwambonambi, Zululand
Company:	SAPPI Forests
Latitude/Long:	28° 32′ 18″ S 32° 12′ 48″ E
Parent Material:	Recent quaternary sands
Topography:	Level plain
Altitude:	60 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**		**DESCRIPTION**
A1	0 - 40	:	Moist; loamy sand; loose; single-grain; dark grey brown, 10YR 4/2; gradual transition to E.
E	40+	:	Moist; loamy sand; friable; single-grain; yellowish brown, 10YR 6/4; clay lamellae common; becoming paler with depth; few pale orange mottles present from 100 cm +.

(Pit dug to 150 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 40	LmSa	9	3	2	41	39	6	0.23	0.38
E	40+	LmSa	9	3	5	40	37	5	0.07	n.d

SOIL **CHEMICAL PROPERTIES**

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.35	5.50	0.07	0.67	0.34	0.07	0.10	1.25
E	n.d	n.d	n.d	n.d	n.d	n.d.	n.d	n.d

PROFILE 13

Soil:	Fw 1110
Soil Form:	Fernwood
Soil Family:	Penicuik
Soil Taxonomy:	Aquic Ustipsamment
Location:	Salpine, Kwambonambi, Zululand
Company:	SAPPI Forests
Latitude/Long:	28° 33′ 00″ S 32° 11′ 24″ E
Parent Material:	Recent quaternary sands
Topography:	Flat plain
Altitude:	50 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 50 :	Moist; loamy sand; friable; single-grain; dark grey brown, 10YR 4/2; single grain; clear transition to E.
E1	50 - 140 :	Moist; loamy sand; friable to slightly firm; pale diffuse mottling increasing with depth, pale brown 10YR 6/3; single grain;

(Pit dug to 140 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 50	LmSa	8	4	2	37	45	5	0.16	0.26
E	50 - 140	LmSa	8	3	6	38	40	5	0.09	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c$ kg^{-1})				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c$ kg^{-1})	
A1	4.00	5.10	0.05	0.24	0.19	0.25	0.23	0.96
E	4.10	6.60	0.09	0.18	0.33	0.03	0.04	0.67

PROFILE 14

Soil:	Hu 2100
Soil Form:	Hutton
Soil Family:	Hayfield
Soil Taxonomy:	Typic Kandiustult
Location:	Kwambonambi, Zululand
Company:	Mondi Forests
Latitude/Long:	28° 31′ 30″ S 32° 12′ 42″ E
Parent Material:	Berea sandstone
Topography:	Level plain close to old dune ridge
Altitude:	30 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20 :	Moist; sandy loam; friable; dark brown, 10YR 3/3; single grain; clear transition to B1
B1	20 - 40 :	Moist; sandy loam; friable to slightly firm; reddish brown, 5YR 4/3; apedal; diffuse transition to B2
B2	40+ :	Moist; sandy clay loam; slightly firm; yellowish red, 5YR 4/6; apedal

(Pit dug to 120 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SaLm	12	5	4	32	36	11	0.39	0.43
B1	20 - 40	SaLm	15	3	12	25	30	15	0.67	n.d
B2	40+	SaClLm	23	5	12	25	25	10	0.49	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.90	5.95	0.17	0.26	0.51	0.11	0.08	1.13
B1	4.10	6.60	0.06	0.11	0.33	0.16	0.04	0.64
B2	4.15	6.45	0.06	0.39	0.36	0.10	0.05	0.96

PROFILE 15

Soil:	Fw 2110
Soil Form:	Fernwood
Soil Family:	Waterton
Soil Taxonomy:	Typic Ustipsamment
Location:	Teza, Kwambnambi, Zululand
Company:	Mondi Forests
Latitude/Long:	28° 30′ 54″ S 32° 13′ 36″ E
Parent Material:	Recent quaternary sands
Topography:	Level plain
Altitude:	30 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 45 :	Moist; loamy sand; friable; single-grain; black, 10YR 2/1; few mottles in old root channels; gradual transition to E
E1	45+ :	Moist; loamy sand; friable; single-grain; greyish brown, 10YR 5/2; few orange mottles in old root channels

(Pit dug to 120 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 40	LmSa	9	5	6	40	34	6	0.89	1.65
E	40+	LmSa	8	3	5	35	38	11	0.07	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	(KCl)	(H_2O)	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.10	5.80	0.25	1.02	0.48	0.07	0.23	2.05
E	4.65	6.00	0.09	0.47	0.12	0.05	0.04	0.77

PROFILE 16

Soil:	No 1200
Soil Form:	Nomanci
Soil Family:	Overwood
Soil Taxonomy:	Lithic Ustochrept
Location:	Witrivier Plantation, Commondale
Company:	H.L.& H Mining Timber
Latitude/Long:	27° 12′ 24″ S 30° 57′ 30″ E
Parent Material:	Biotite granite
Topography:	Upper midslope
Altitude:	980 m
Vegetation:	Newly established *E. grandis* plantation (previously grassveld)

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 15 :	Dry; very hard; structureless to very weak, fine sub-angular blocky, hardsetting; slightly bleached; sandy clay loam; dark greyish brown, 10 YR 4/2, (moist: very dark grey, 10 YR 3/1); clear transition to A2.
A2	15 - 40 :	Moist; loose; apedal; sandy clay loam; common, smooth small gravel; dark yellowish brown, 10 YR 3/4, (dry, dark greyish brown, 10 YR 3/2); clear transition to B1/C.
B1/C	40 + :	Moist; very firm; clay; massive; red, 2.5 YR 4/8; few clay cutans; tonguing into granitic saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 15	SaClLm	24	6	11	19	21	19	1.25	2.36
B1	15 - 40	SaClLm	26	6	12	16	16	24	0.73	n.d
B2/C	40+	Cl	42	8	12	14	11	13	1.02	1.35

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. Acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.95	6.45	0.10	2.68	1.33	0.55	0.09	4.75
A2	4.75	6.55	0.11	2.02	1.48	0.11	0.16	3.88
B1	4.7	6.45	0.14	2.06	2.43	0.11	0.24	4.98

PROFILE 17

Soil:	Hu 1200
Soil Form:	Hutton
Soil Family:	Kelvin
Soil Taxonomy:	Typic Kandiustult
Location:	Witrivier plantation (Kohlmeyer), Commondale
Company:	H,L & H Mining Timber
Latitude/Long:	27° 13′ 48″ S 30° 59′ 00″ E
Parent Material:	Biotite granite
Topography:	Level plateau
Altitude:	1050 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 20 :	Moist; loose to friable; apedal; (N.B. very hard when dry); sandy clay loam; dark reddish brown, 5 YR 3/3, (dry: 5 YR 4/3); diffuse transition to B1.
B1	20 - 70 :	Dry; very firm; apedal; sandy clay loam; dark reddish brown, 5 YR 3/3, (moist, 10 YR 3/4); clear transition to B2.
B2	70+ :	Moist; slightly firm; sandy clay; red, 2.5 YR 4/8;

N.B. A crust had developed on soils in the vicinity and evidence of surface wash and erosion following tillage

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SaClLm	26	3	7	14	30	20	0.78	1.49
B1	20 - 70	SaClLm	29	3	3	14	29	22	0.84	1.07
B2	70+	SaCl	47	3	4	10	17	19	0.84	0.65

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. Acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.30	5.05	0.10	1.85	0.38	0.11	0.81	3.25
B1	4.25	5.25	0.10	1.55	0.36	0.13	1.08	3.22
B2	4.45	5.35	0.10	1.52	0.71	0.26	0.79	3.38

PROFILE 18

Soil:	Ia 1200
Soil Form:	Inanda
Soil Family:	Highlands
Soil Taxonomy:	Typic Kanhaplustult
Location:	Tweepoort, Amsterdam
Company:	SilvaCel
Latitude/Long:	26° 38′ 18″ S 30° 43′ 42″ E
Parent Material:	Leucocratic Granite
Topography:	Gently sloping midslope
Altitude:	1460 m
Vegetation:	*E. nitens* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20 :	Moist; soft to slightly firm; apedal; (N.B. dry crust on surface); brown, 7.5 YR 4/4, (dry, reddish yellow, 7.5 YR 6/6); gradual transition to A2.
A2	20 - 30 :	Moist; hard quartz stone line; 50% stones; apedal; reddish brown, 5 YR 4/4; abrupt transition to B1.
B1	30 - 70 :	Moist; firm; apedal; red, 2.5 YR 4/8; diffuse transition to B2.
B2	70 - 110:	Moist; slightly firm; apedal, some granitic saprolite; light red, 2.5 YR 6/8; diffuse transition with C.
C	110+ :	Granitic saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SaClLm	28	8	8	31	17	8	1.14	2.42
A2	20 - 30	SaClLm	24	6	11	28	15	16	1.23	1.50
B1	30 - 70	ClLm	34	9	15	23	11	8	1.04	0.71
B2	70 - 110	Lm	25	17	28	17	7	6	0.81	0.29
C	110 +	Lm	20	22	26	20	8	4	0.00	n.d

PROFILE 18 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations (cmol$_c$ kg^{-1})				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	(cmol$_c$ kg^{-1})	
A1	3.70	4.65	0.07	0.44	0.38	0.16	1.50	2.55
A2	3.80	4.75	0.02	0.22	0.14	0.08	1.60	2.05
B1	4.10	5.10	0.00	0.16	0.17	0.00	1.40	1.73
B2	4.20	5.30	0.01	0.10	0.13	0.00	1.84	2.06
C	4.25	5.75	0.07	0.13	0.08	0.01	2.17	2.46

PROFILE 19

Soil: Kp 1100
Soil Form: Kranskop
Soil Family: Fordoun
Soil Taxonomy: Humic Xanthic Haplustox
Location: Lions Glen, Amsterdam
Company: SilvaCel
Latitude/Long: 26° 32′ 06″ S 30° 41′ 54″ E
Parent Material: Ultra mafic: gabbro, norite
Topography: Level upland plateau
Altitude: 1550 m
Vegetation: *E. smithii* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 25 :	Moist; soft; apedal; dark brown, 10 YR 3/3, (dry, yellowish brown, 10 YR 5/4); clear transition to B1.
B1	25 - 50 :	Moist; firm; apedal; dark yellowish brown, 10 YR 4/6; diffuse transition to B2.
B2	50 - 90 :	Moist; firm; apedal; yellowish brown, 10 YR 5/8; diffuse transition to B3.
B3	90 + :	Moist; firm; fine, weak subangular blocky; few Mn concretions; yellowish brown, 10 YR 5/8; some weathering material viz Fe nodules.
C	110+ :	Diabase saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 25	Cl	65	7	20	4	1	1	4.36	4.13
B1	25 - 50	Cl	59	9	27	3	1	1	3.26	1.56
B2	50 - 90	Cl	58	11	23	10	7	6	2.39	0.58

PROFILE 19 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.10	5.65	0.05	1.50	1.02	0.15	0.95	3.67
B1	4.65	5.05	0.02	1.14	0.76	0.07	0.08	2.07
B2	5.15	5.40	0.03	0.60	0.44	0.03	0.05	1.15

PROFILE 20

Soil:	Kp 1100
Soil Form:	Kranskop
Soil Family:	Fordoun
Soil Taxonomy:	Typic Haplustox
Location:	Woodstock Plantation, Lothair
Company:	SAPPI Forests (previously Lotzaba)
Latitude/Long:	26° 12′ 12″ S 30° 27′ 18″ E
Parent Material:	Granitic gneiss
Topography:	Level upland plateau
Altitude:	1752 m
Vegetation:	*E. nitens* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 30 :	Dry; very hard; sandy clay; dark brown, 10 YR 3/3; apedal to weak, very fine sub-angular blocky; clear to gradual boundary to B1.
B1	30 - 90 :	Dry; hard; clay; yellowish brown, 10 YR 5/8 (moist: strong brown 7.5 YR 5/6); many (10%) coarse angular quartz fragments, 1-3 mm; diffuse stone line at 60 - 70 cm; apedal; diffuse boundary to B2.
B2	90 - 120:	Dry; hard; apedal; strong brown 7.5 YR 5/6 (moist: yellowish red, 5 YR 5/8 some quartz fragments; <5% granite saprolite; diffuse boundary to C.
C	120+ :	Granitic gneiss saprolite.

(Pit dug to 140 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	SaCl	43	6	9	9	12	21	2.56	4.23
B1	30 - 90	Cl	45	6	10	6	6	27	1.40	0.97
B2	90 - 120	Cl	49	14	21	10	3	3	1.34	n.d

PROFILE 20 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.15	5.35	0.16	1.11	0.14	0.27	1.61	3.29
B1	4.35	6.15	0.23	1.10	0.08	0.16	0.75	2.32
B2	4.85	7.00	0.60	1.16	5.56	0.88	0.07	8.27

PROFILE 21

Soil:	Cv 1100
Soil Form:	Clovelly
Soil Family:	Twyfelaar
Soil Taxonomy:	Lithic Haplustox
Location:	Warburton
Company:	MONDI Forests
Latitude/Long:	26° 22′ 12″ S 30° 27′ 12″ E
Parent Material:	Ecca sandstone
Topography:	Level upland plateau
Altitude:	1675 m
Vegetation:	*E. nitens* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 30 :	Dry; soft; sandy clay loam; (dark brown, 10 YR 3/3); apedal; clear to gradual boundary to B1.
B1	30 - 80 :	Dry; slightly hard; sandy clay loam; (yellowish brown, 10 YR 5/8); apedal; clear transition into weathering sandstone saprolite.
C	80+ :	Weathering saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	SaClLm	34	7	9	18	17	15	1.14	1.37
B1	30 - 80	SaClLm	31	7	12	15	16	19	1.02	0.92

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.95	5.70	0.06	0.19	0.11	0.00	1.40	1.76
B1	4.05	4.30	0.00	00.17	0.10	0.04	1.12	1.43

PROFILE 22

Soil:	Hu 1200
Soil Form:	Hutton
Soil Family:	Kelvin
Soil Taxonomy:	Rhodic Kanhaplustult
Location:	Glenthorpe plantation, Barberton
Company:	SAPPI Forests (previously Lotzaba)
Latitude/Long:	25° 43′ 18″ S 30° 50′ 18″ E
Parent Material:	Hornblende biotite granite / diabase
Topography:	Gentle midslope
Altitude:	880 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 20:	Moist; sandy clay loam; slightly hard to hard; weak, very fine sub-angular blocky; few clay skins; yellowish red, 5 YR 5/6 (dry: red, 2.5YR 4/6); abrupt transition to B1.
B1	20 - 85:	Moist; friable; clay; apedal (very weak coarse prismatic); red, 2.5 YR 4/6, (dry: red, 2.5 YR 5/8); few small quartz grains; gradual boundary to B2.
B2	85+:	Moist; very firm; clay; apedal (very weak coarse prismatic); red, 2.5 YR 4/6, (dry: red, 2.5 YR 5/8); diabase and granitic saprolite in places.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 20	SaClLm	32	2	6	13	24	23	1.13	1.21
B1	20 - 85	Cl	52	2	6	10	13	17	1.38	0.55

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	4.25	5.85	0.18	0.87	0.16	0.14	0.89	2.24
B1	4.35	5.65	0.14	0.55	0.09	0.16	1.75	2.69

PROFILE 23

Soil:	Sw 1211
Soil Form:	Swartland
Soil Family:	Shangoni
Soil Taxonomy:	Rhodic Kanhaplustalf
Location:	Glenthorpe Estate, Barberton
Company:	SAPPI Forests (formerly Lotzaba)
Latitude/Long:	25° 42′ 06″ S 30° 50′ 30″ E
Parent Material:	Diabase in hornblende biotite granite
Topography:	Midslope
Altitude:	900 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 35 :	Dry; hard; moderate, medium sub-angular blocky; dark reddish brown, 5 YR 3/4; gradual transition to B1.
B1	35 - 80 :	Moist; very firm; moderate coarse sub-angular blocky; dark red, 2.5 YR 3/6; frequent cutans on ped faces; few diabase and quartz fragments in upper B1; diffuse transition to B2.
B2	80 - 110 :	Moist; firm; weak, fine sub-angular blocky; red 2.5YR 4/8; diffuse transition to C.
B3	110 + :	Moist; firm; fine, weak subangular blocky; few Mn concretions; yellowish brown, 10 YR 5/8; some weathering material viz Fe nodules; grading into granitic saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 35	SaClLm	34	7	13	18	19	9	1.50	4.13
B1	35 - 80	Cl	64	4	16	7	6	3	1.24	n.d
B2	80 - 90	Cl	43	6	28	9	8	6	0.82	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	5.20	6.50	0.14	4.79	0.73	0.03	0.05	5.74
B1	4.90	6.35	0.18	3.87	0.80	0.10	0.08	5.03
B2	4.80	6.35	0.16	3.40	5.03	0.27	0.03	8.89

PROFILE 24

Soil:	Sw 2111
Soil Form:	Swartland
Soil Family:	Adelaide
Soil Taxonomy:	Typic Kanhaplustalf
Location:	Boschfontein Estate, Barberton
Company:	SAPPI Forests (formerly Lotzaba)
Latitude/Long:	25° 45′ 24″ S 30° 52′ 48″ E
Parent Material:	Hornblende biotite granite / diabase
Topography:	Midslope
Altitude:	880 m
Vegetation:	*E. grandis* plantation

HORIZON	**DEPTH (cm)**	**DESCRIPTION**
A1	0 - 30 :	Moist; very firm; fine, medium sub-angular blocky; very dark grey, 5 YR 3/1; wavy, clear transition to B1 via stone line.
(A2)	30 - 35 :	Stone line; few diabase and quartz fragments; abrupt transition to B2.
B1	35 - 60 :	Moist; very firm; strong brown, 7.5YR 4/6; moderate, coarse angular blocky; pedocutanic horizon; many distinct strong brown cutans (7.5YR 4/4); diffuse transition to B2.
B2	60 - 110 :	Moist; firm; fine, moderate subangular blocky; few Mn concretions; slightly variegated colour matrix; yellowish red, 5 YR 5/8; some dark red cutans on peds (2.5YR 3/6); grading into granitic saprolite.
C	110+ :	Granitic saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	SaClLm	31	5	12	11	14	27	0.82	1.94
B1	35 - 60	ClLm	38	5	12	10	11	23	0.80	1.46
B2	60 - 110	Cl	48	12	16	5	7	12	0.71	n.d

PROFILE 24 (continued)

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	5.90	6.40	0.10	5.84	1.26	0.55	0.13	7.88
B1	4.30	5.20	0.14	0.92	0.22	0.25	0.72	2.25
B2	4.35	6.10	0.21	0.96	1.87	0.26	0.27	3.57

PROFILE 25

Soil:	Ia 1200
Soil Form:	Inanda
Soil Family:	Highlands
Soil Taxonomy:	Typic Kandihumult
Location:	Ramanas plantation, Graskop
Company:	MONDI Forests
Latitude/Long:	24° 52′ 05″ S 30° 58′ 48″ E
Parent Material:	Biotite granite
Topography:	Midslope
Altitude:	960 m
Vegetation:	*E. grandis* plantation

HORIZON	DEPTH (cm)	DESCRIPTION
A1	0 - 30 :	Dry; slightly hard; weak, dark brown, 10 YR 3/3; weak, medium sub-angular blocky; clear to gradual boundary to B1.
B1	30 - 90 :	Dry; hard; yellowish red; 5 YR 5/6 ; few (10%) coarse quartz fragments, 1 to 5 mm; diffuse stone line at 30 - 40 cm; apedal; diffuse boundary to B2.
B2	90 - 110:	Dry; slightly hard; apedal; red 2.5YR 5/6; some granitic saprolite; diffuse boundary to C.
C	110+ :	Granitic saprolite.

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 30	SaClLm	34	3	8	6	12	37	1.81	2.85
B1	30 - 90	ClLm	40	6	10	8	9	27	n.d	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c$ kg^{-1})				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c$ kg^{-1})	
A1	4.05	5.05	0.14	0.55	0.23	0.11	0.95	1.98
B1	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

PROFILE 26

Soil:	Ma 1100
Soil Form:	Magwa
Soil Family:	Glenesk
Soil Taxonomy:	Humic Xanthic Haplustox
Location:	Ramanas plantation, Graskop
Company:	MONDI Forests
Latitude/Long:	24° 50′ 48″ S 30° 59′ 48″ E
Parent Material:	Biotite granite
Topography:	Lower Midslope
Altitude:	860 m
Vegetation:	*P patula* plantation

HORIZON	DEPTH (cm)		DESCRIPTION
A1	0 - 35	:	Moist; friable; brown, 10 YR 4/3; apedal; clear boundary to B1.
B1	35 +	:	Moist; slightly firm; yellowish brown; 10. YR 5/6; apedal; diffuse boundary to B2.

(Pit dug to 110 cm)

SOIL PHYSICAL PROPERTIES

Horizon	Depth (cm)	Texture	PARTICLE SIZE ANALYSIS (%)						Organic Carbon (%)	
			Clay	Silt		Sand			Loss-on-ignition (LOI)	Walkley-Black (WB)
				F	C	F	M	C		
A1	0 - 35	SaClLm	30	3	8	7	18	35	2.85	3.42
B1	35+	ClLm	35	7	11	9	10	28	n.d	n.d

SOIL CHEMICAL PROPERTIES

Horizon	pH		Exchangeable Cations ($cmol_c\ kg^{-1}$)				Exch. acidity	ECEC
	KCl	H_2O	Na	Ca	Mg	K	($cmol_c\ kg^{-1}$)	
A1	3.85	4.75	0.15	0.53	0.12	0.08	1.86	2.74
B1	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

APPENDIX 2

Laboratory methods of analysis.

APPENDIX 2: LABORATORY METHODS OF ANALYSIS

All samples were sieved through a 2mm screen and air-dried for at least 48 hours before being bottled. All subsequent determinations were made on air-dry screened soil. The results were, however, expressed in terms of an oven-dry mass which was calculated by drying the air-dry soil at 105°C and determining the air-dry water content as a percentage of oven dry soil.

2.1 Particle size distribution

The pipette method was used to determine particle size distribution. Air-dried soil samples (10 g) were pretreated with 10 ml of 30% H_2O_2 to remove organic matter by oxidation. Dispersion of the soil samples was achieved by the addition of Calgon (sodium hexametaphosphate and sodium carbonate solution) and the soil slurries subjected to ultrasound (20 kHz) at 350 Watts for approximately three minutes using a probe sonicator (Braun Ultrasonic-Homogeniser Labsonic U).

Clay (< 0.002 mm), fine silt (0.002 to 0.02 mm) and coarse silt (0.02 to 0.05 mm) fractions were determined by sedimentation and pipette sampling and expressed as a percentage of oven-dried soil (Day, 1965). The sand fraction was determined by dry sieving. The residue was decanted into a small beaker and then dried overnight at 105°C and passed through two sieves; 500 micron for coarse sand (>0.5 mm) and 250 micron for medium sand (0.25 to 0.5 mm). The remainder passing through both sieves was classed as fine sand and very fine sand (0.05 to 0.25 mm).

2.2 Soil pH

Soil pH was determined three times for each sample. The equilibrating solutions used were deionised water, and 1M KCl. In each case 10 g of soil was shaken in a stoppered vial with 25 ml of the equilibrating solution to give a soil:solution ratio of 1:2.5. The pH of the resultant supernatant was read using a standard glass electrode (Metrohm Hersiau E396B) after the vial had been left to stand overnight.

2.3 Organic carbon by loss-on-ignition (LOI)

Thermogravimetric loss-on-ignition was determined by the ignition of the soil sample at 430°C for at least 4 hours (Donkin, 1991).

2.4 Organic matter determination (WB)

The oxidizable organic carbon fraction in the soil was determined using the wet oxidation technique according to Walkley (1947), commonly referred to as the Walkley-Black method. Air-dry soil was ground to pass a 0.5 mm screen and then digested in a potassium dichromate/sulphuric acid mixture in which the organic matter is oxidised. Soil organic matter content is then determined by back-titration of the excess dichromate, using a 0.5N ferrous ammonium sulphate solution.

2.5 Exchangeable cations

Soil samples were equilibrated with 1M ammonium acetate (pH 7) for 10 minutes in stoppered centrifuge bottles on a tumbler. The resulting slurry was then centrifuged to 3000 rpm and then filtered through Whatman 41 filter paper. The filtrate was suitably diluted and appropriate ionisation suppressants were added. The basic cations in the solution (calcium, magnesium, potassium and sodium) were determined using atomic absorption and flame emission spectroscopy (Varian AA 10B instrument), and expressed $cmol_c\ kg^{-1}$ soil.

2.6 Exchangeable acidity

Soil samples were equilibrated with unbuffered 1N potassium chloride, centrifuged at 3000 rpm and then filtered through Whatman 41 filter paper. An aliquot of filtrate was titrated against a standardised NaOH solution using an autotitrator. The potentiometric endpoint was set at a pH of 8.40. Exchangeable acidity is expressed in terms of $cmol_c\ kg^{-1}$ soil.

2.7 Effective cation exchange capacity (ECEC)

The effective cation exchange capacity (ECEC) was calculated as the sum of the exchangeable cations and the exchangeable acidity measured above.

$$ECEC = \Sigma \text{ exchangeable } (Ca^{2+} + Mg^{2+} + K^{+} + Na^{+} + \text{acidity}) \text{ cmol}_c \text{ kg}^{-1} \text{ soil}$$

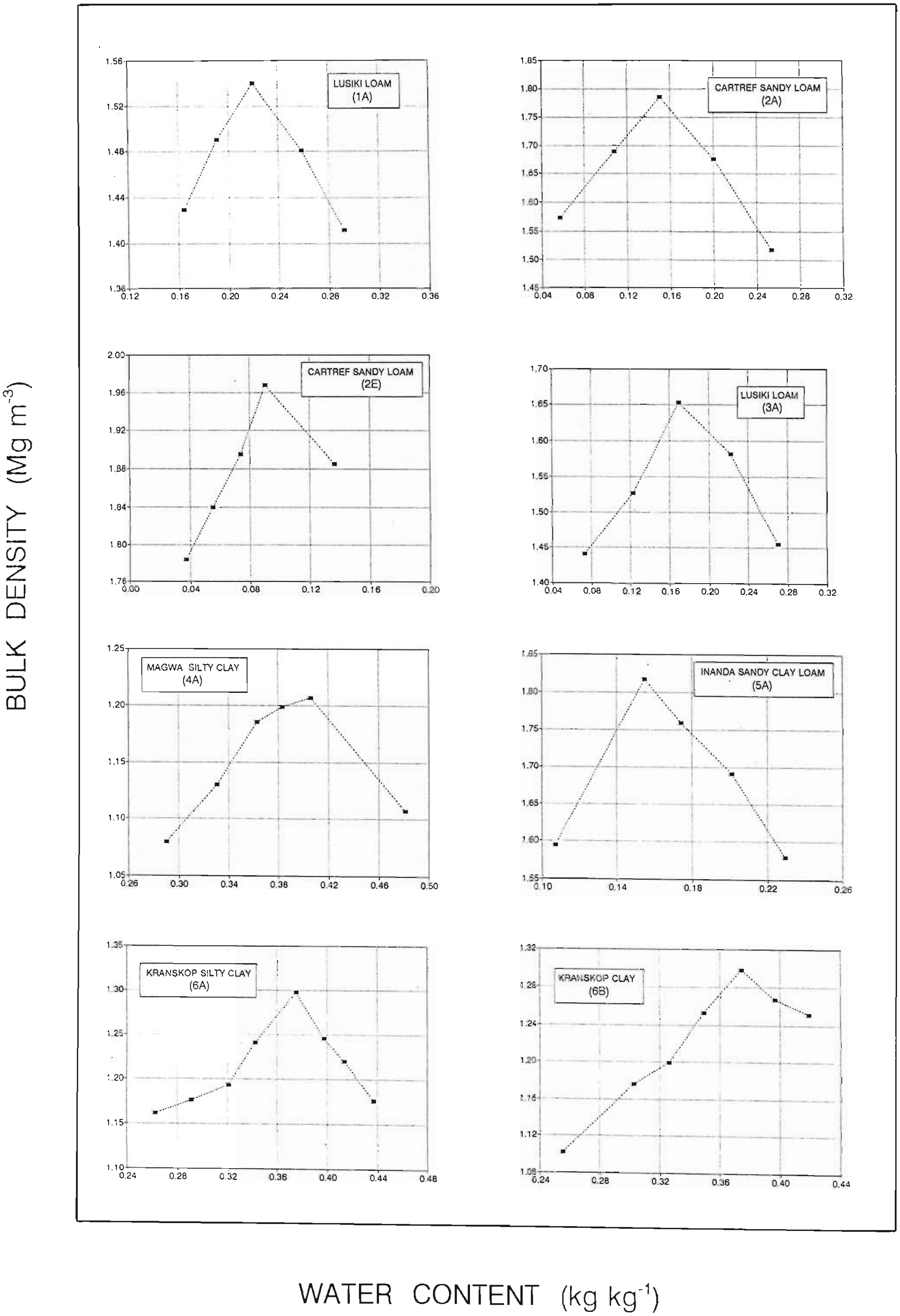
2.8 Dispersible clay

The method used for determining percentage water dispersible clay was a modification of the method of Rengasamy (1983) and Miller and Baharuddin (1987). Soils were passed through a 2 mm sieve and air dried. 20 g samples of soil were then placed into 300 ml glass centrifuge cylinders to which 100 ml of distilled water was added to give a soil:water ratio of 1:5. The soil solutions were then subjected to end-over-end shaking by mechanical shaking for two hours. The amount of dispersible clay was determined by pipetting 25 ml aliquots of suspension after an appropriate settling time and calculating the amount of clay in suspension after drying in the oven at 110°C overnight. The results were expressed as a percentage of the total soil mass.

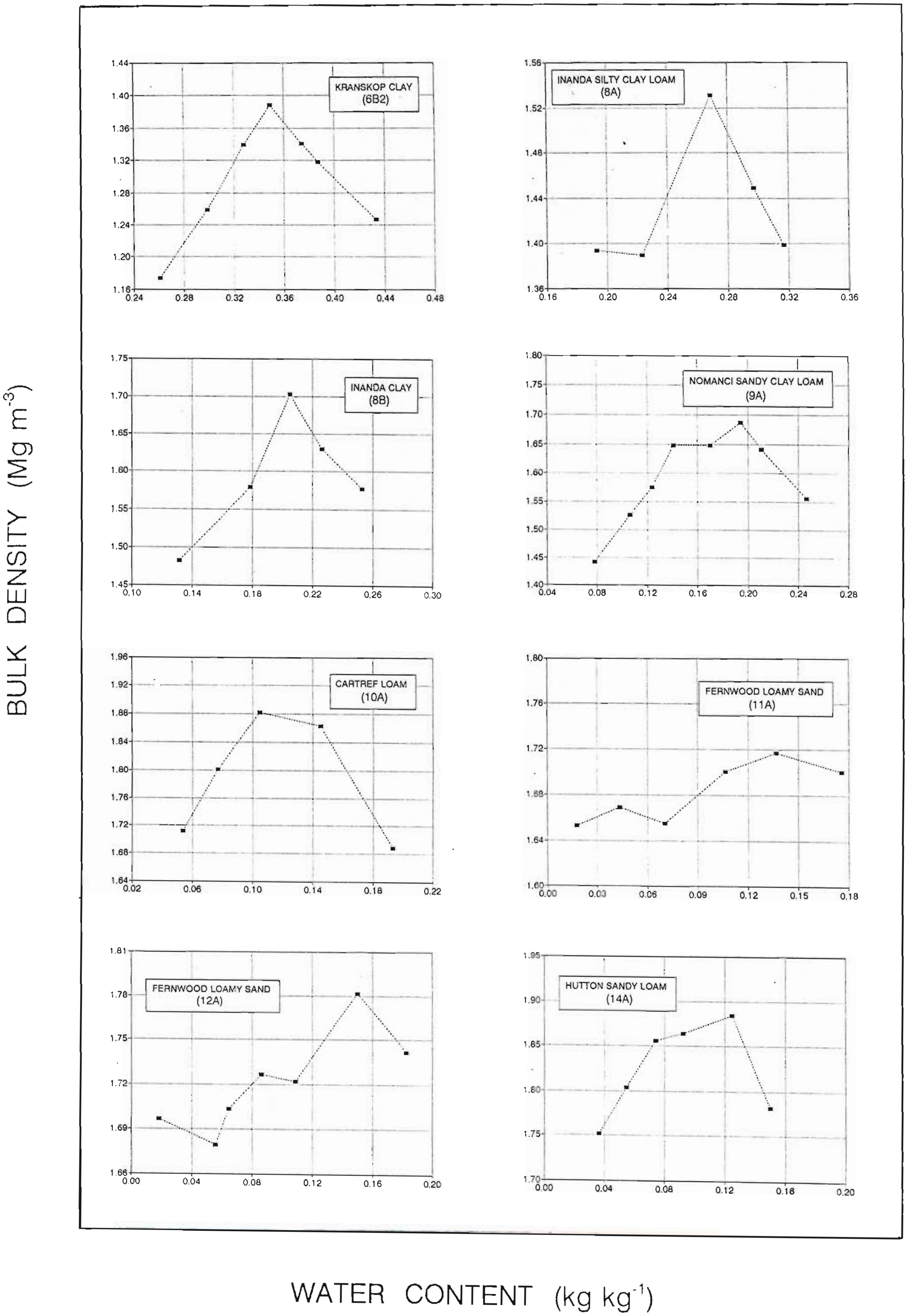
APPENDIX 3

Plots of bulk density (MBD) versus water content determined during Proctor compaction tests for all the soils in the study.

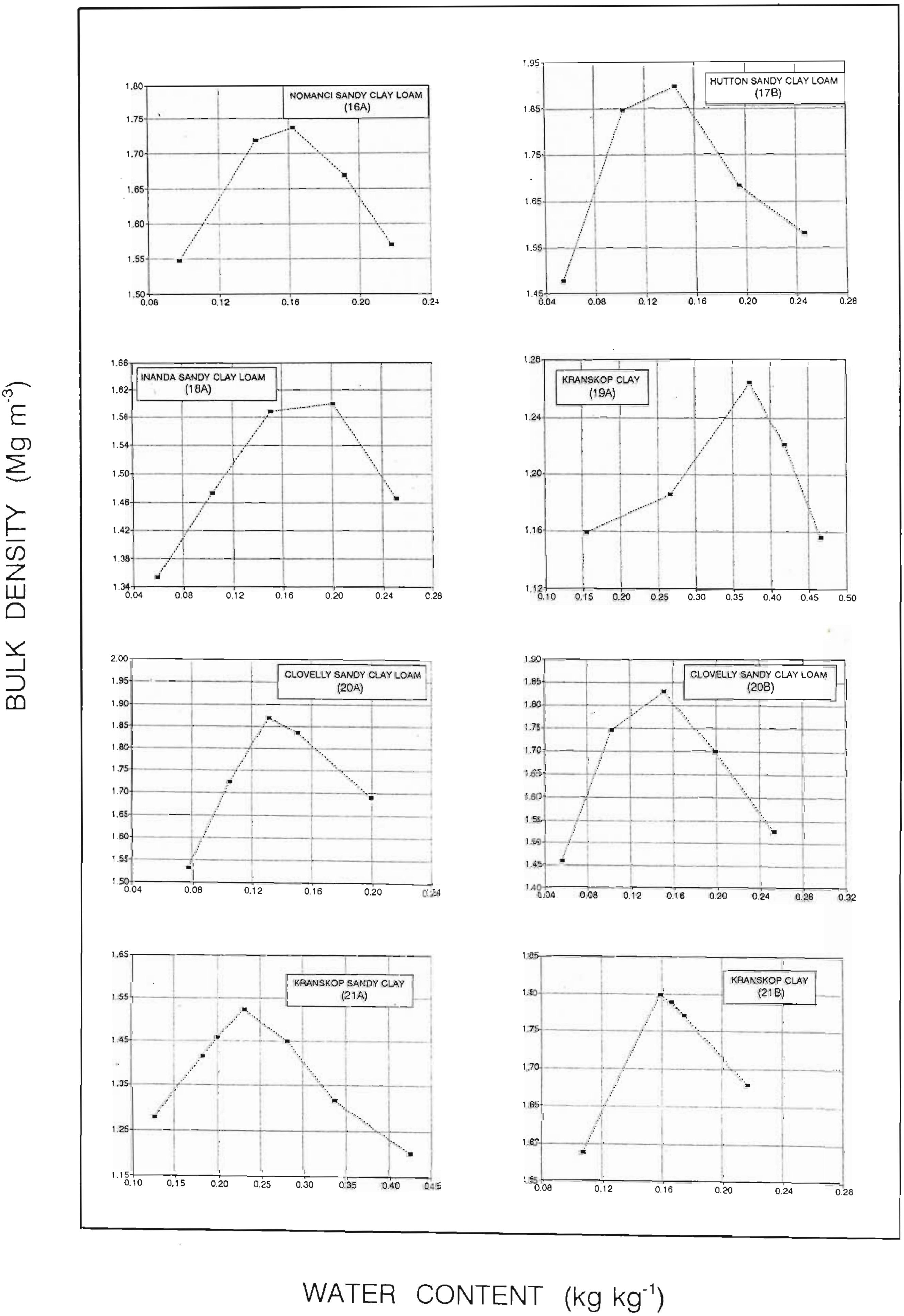
Appendix 3: The relationship between bulk density and water content for selected forestry soils obtained by the Proctor test. MBD values occur at the peak of the curve.



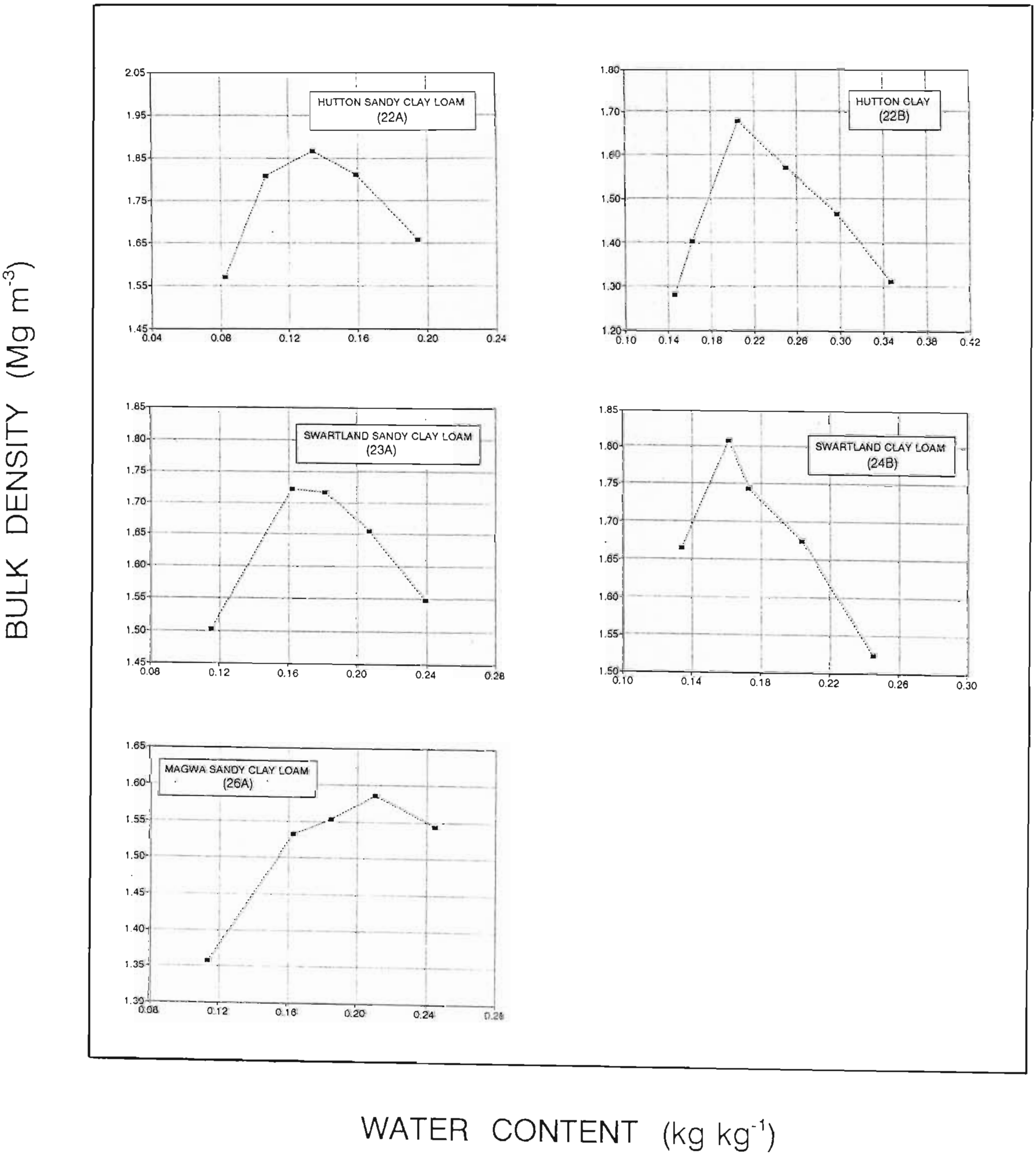
Appendix 3 (continued)



Appendix 3 (continued)



Appendix 3 (continued)



APPENDIX 4

Correlation matrix of relationships between selected soil physical properties.

Appendix 4: Correlation matrix of relationships between selected soil physical properties.

	CLAY + SILT	ORG C (LOI)	ORG C (WB)	CLAY	FINE SILT	COARSE SILT	FINE SAND	MEDIUM SAND	COARSE SAND	SKEW	KURT	GMD	GSDEV
CLAY + SILT	1.0000 **												
ORG C (LOI)	0.8117 **	1.0000 **											
ORG C (WB)	0.5826 **	0.7784 **	1.0000 **										
CLAY	0.8657 **	0.7371 **	0.4569	1.0000 **									
FINE SILT	0.6108 **	0.4082	0.3661	0.1615	1.0000 **								
COARSE SILT	0.8368 **	0.6668 **	0.5754 **	0.4689 *	0.8271 **	1.0000 **							
FINE SAND	-0.7944 **	-0.6672 **	-0.4648 *	-0.8688 **	-0.1455	-0.5294 *	1.0000 **						
MEDIUM SAND	-0.9379 **	-0.7338	-0.5913 **	-0.8233 **	-0.5457 **	-0.7804 **	0.7982 **	1.0000 **					
COARSE SAND	-0.2170	-0.1891	-0.0745	0.0340	-0.5733 **	-0.3345	-0.3586	-0.0135	1.0000 **				
SKEW	0.9841 **	0.7838 **	0.5373 **	0.9179 **	0.5232 *	0.7438 **	-0.8151 **	-0.9328 **	-0.1677	1.0000 **			
KURT	0.2496	0.3228	0.0572	0.1034	0.3625	0.2941	0.0777	0.0078	-0.7001 **	0.1991	1.0000 **		
GMD	-0.9121 **	-0.6830 **	-0.5354 **	-0.8602 **	-0.4603	-0.6870 **	0.8023 **	0.9334 **	0.0074	0.1315	0.1315	1.0000 **	
GSDEV	0.1535	0.0915	0.1394	0.4712 *	-0.4161	-0.2077	-0.4953 *	-0.3503	0.6507 **	-0.6887 **	-0.6887 **	-0.4283	1.0000 **
	CLAY + SILT	ORG C (LOI)	ORG C (WB)	CLAY	FINE SILT	COARSE SILT	FINE SAND	MEDIUM SAND	COARSE SAND	SKEW	KURT	GMD	GSDEV

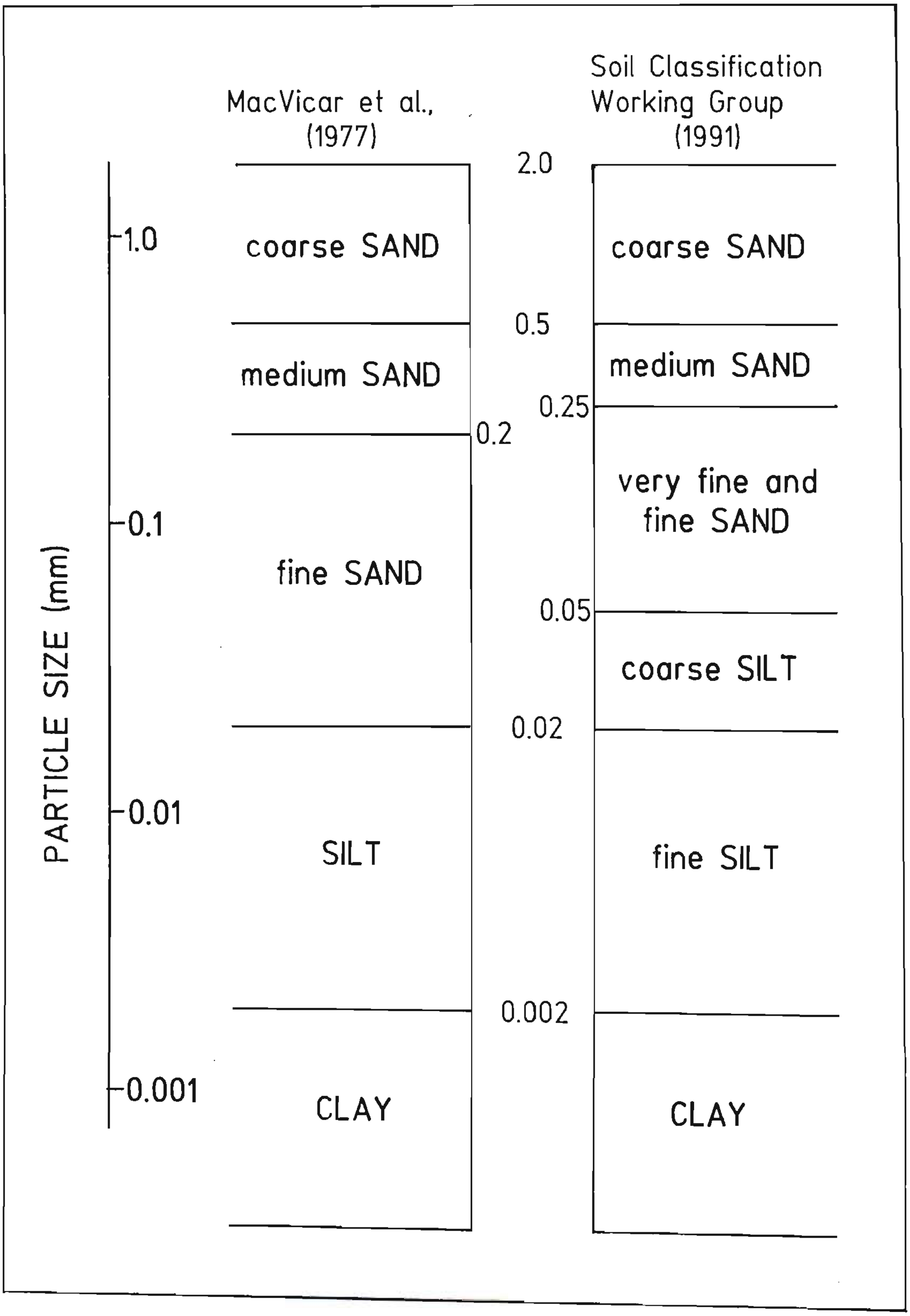
* Denotes significance at the 5% probability level

** Denotes significance at the 1% probability level

APPENDIX 5

The change in particle size limits from the 1977 South African soil classification to the 1991 classification.

Appendix 5: The change in particle size limits from the 1977 South African soil clasiification[1] to the 1991 classification[2].

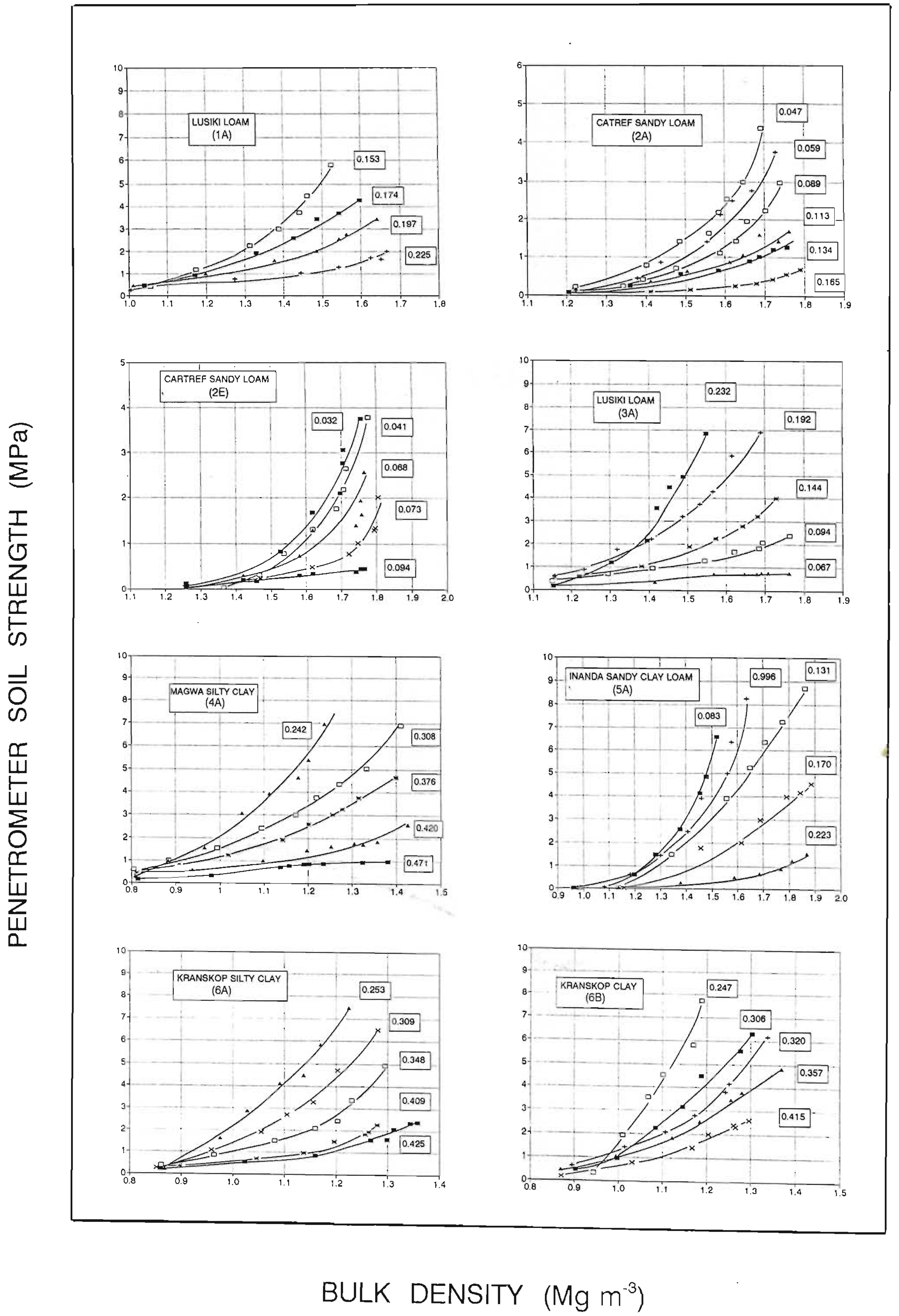


1 Macvicar *et al.*, (1977)
2 Soil classification working group (1991)

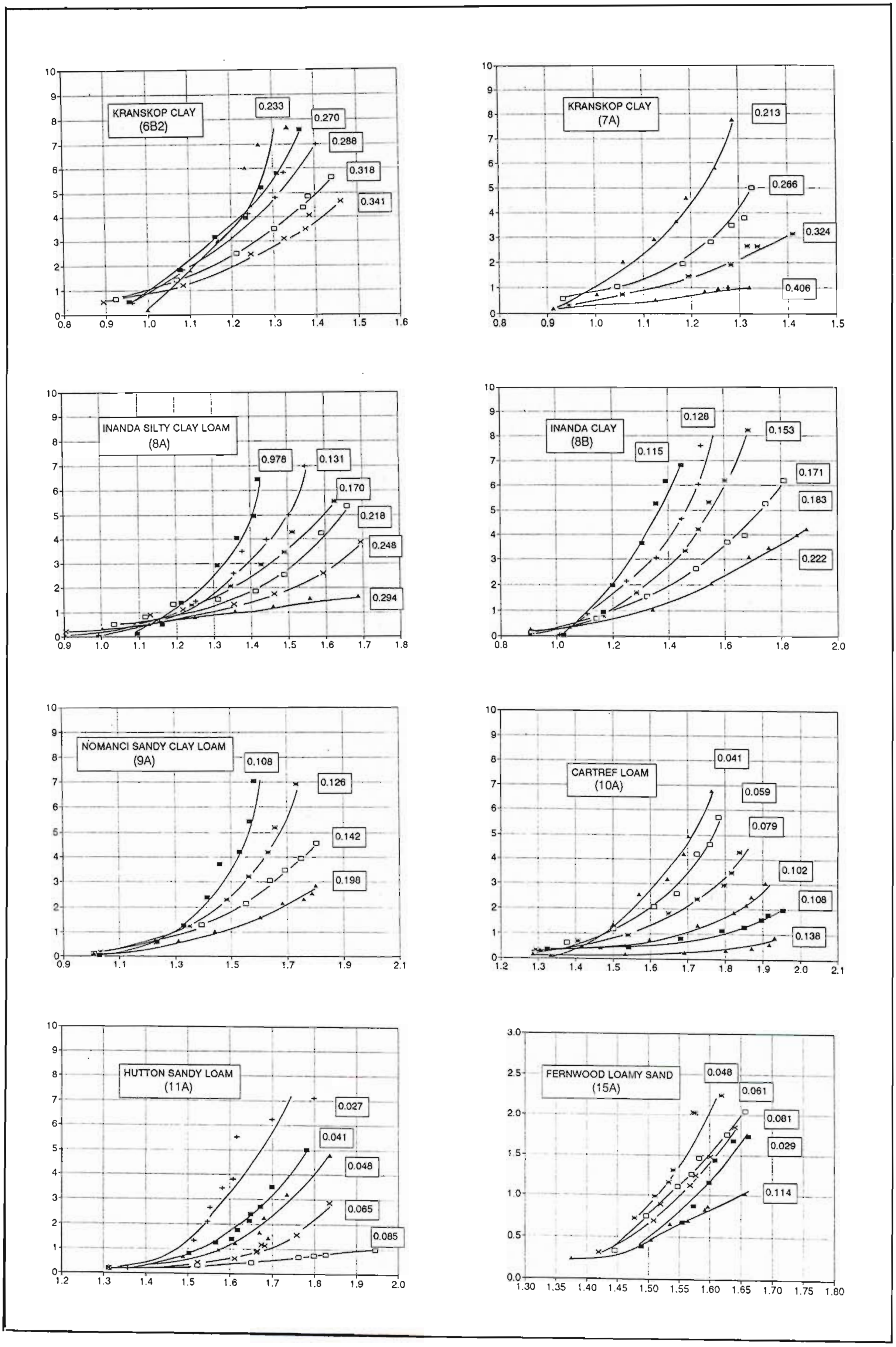
APPENDIX 6

Plots of penetrometer soil strength (PSS) versus bulk density at a range of water contents for all the soils in the study. Water contents are expressed on a mass basis ($kg\ kg^{-1}$).

Appendix 6: Plots of penetrometer soil strength (PSS) versus bulk density at a range of water contents for all the soils in the study. Water contents are expressed on a mass basis (kg kg^{-1}).



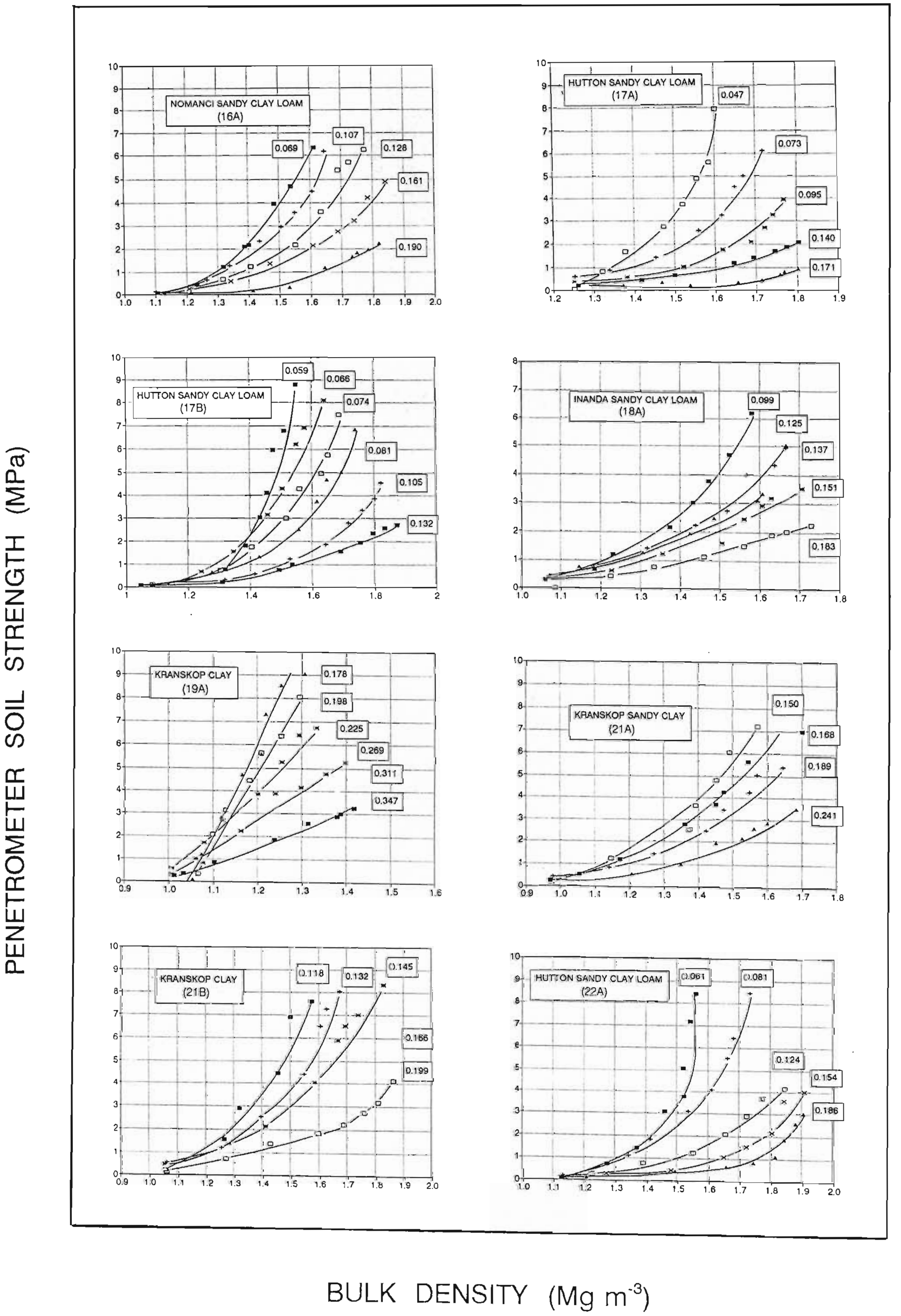
Appendix 6: (continued)



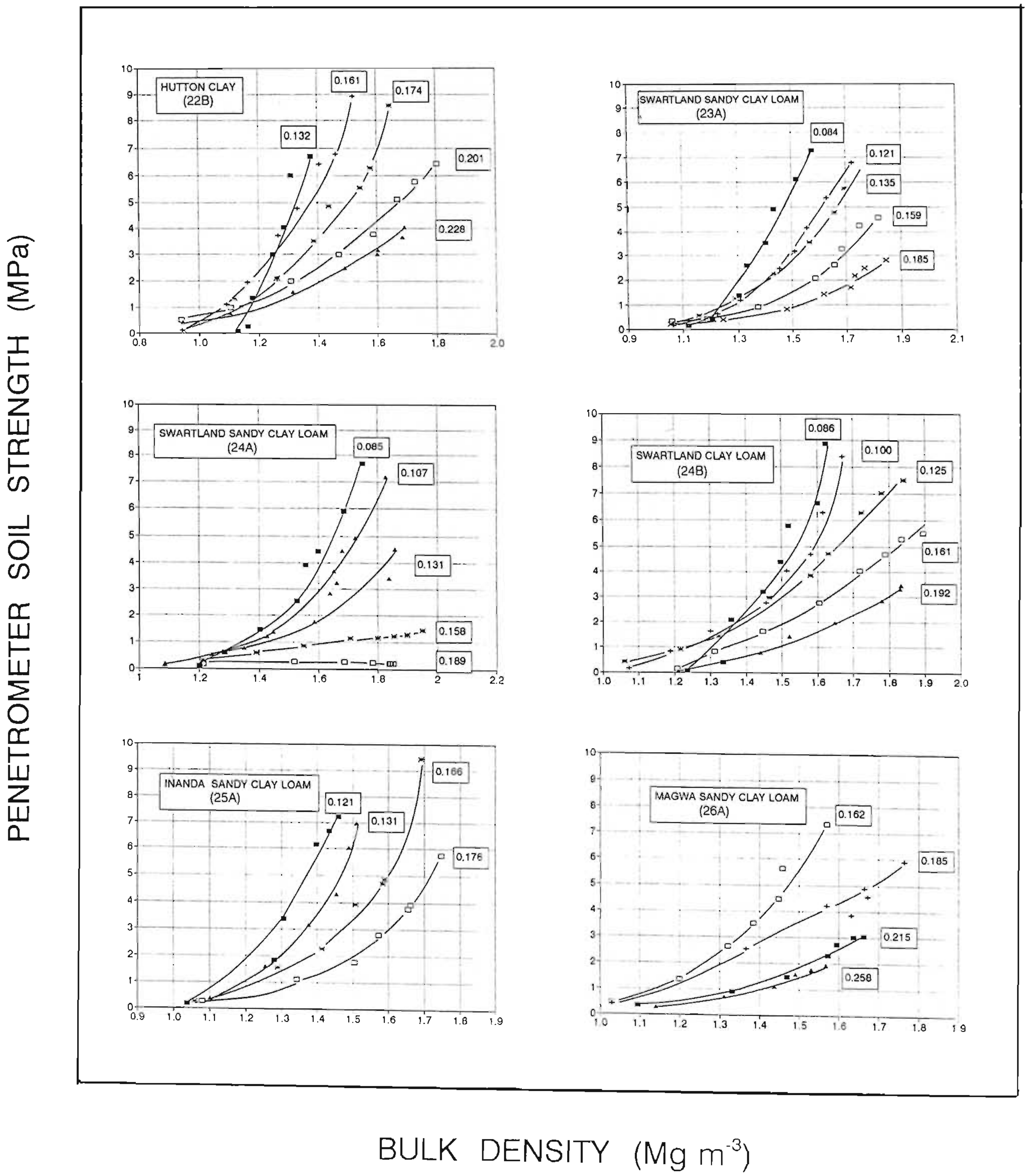
PENETROMETER SOIL STRENGTH (MPa)

BULK DENSITY (Mg m^{-3})

Appendix 6: (continued)

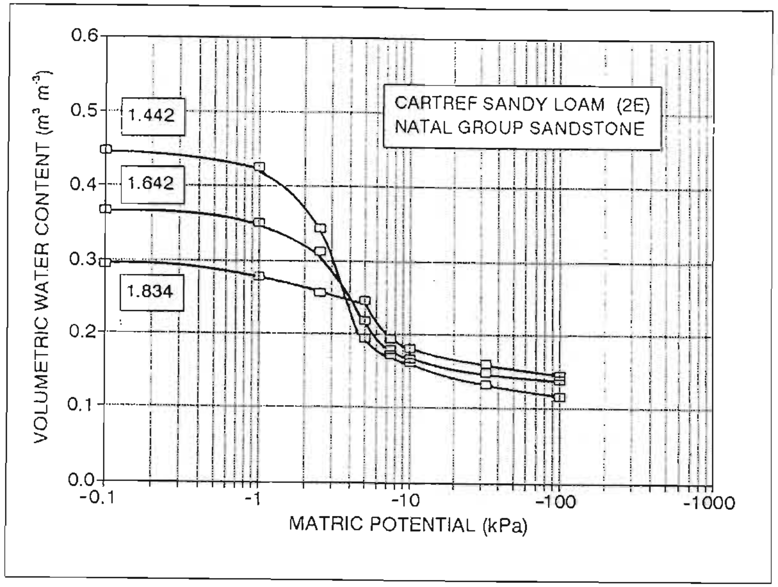


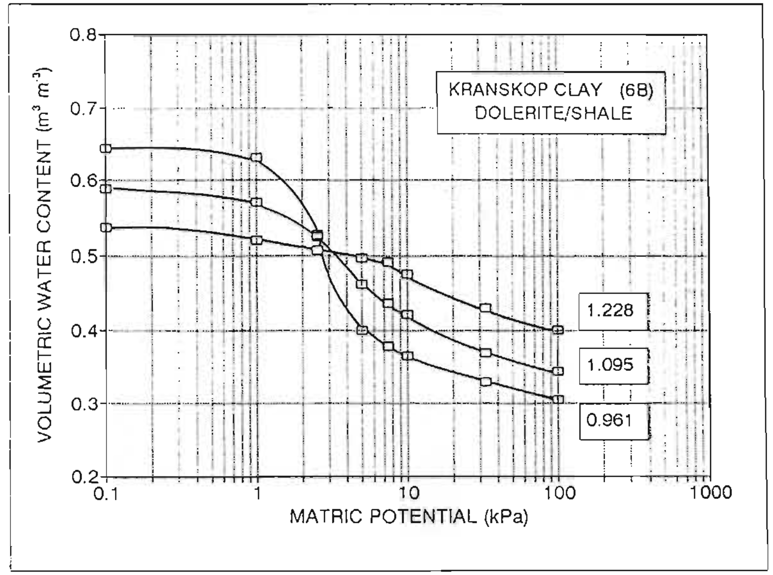
Appendix 6: (continued)

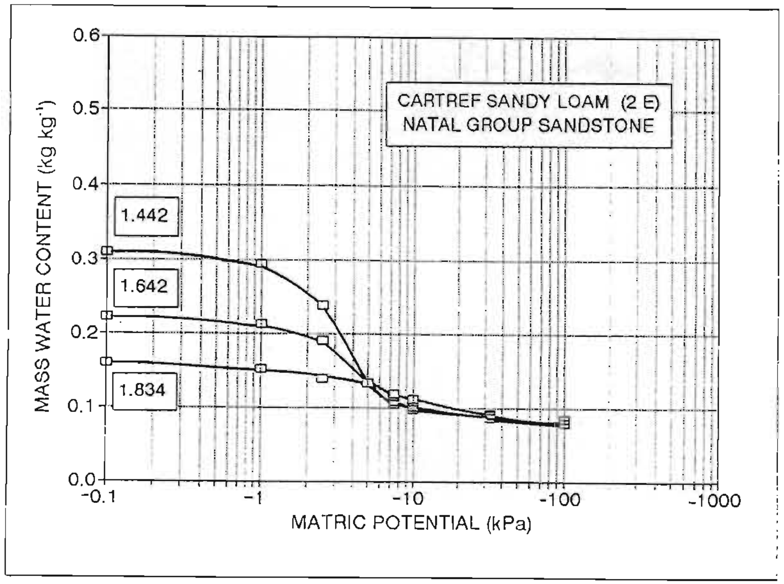


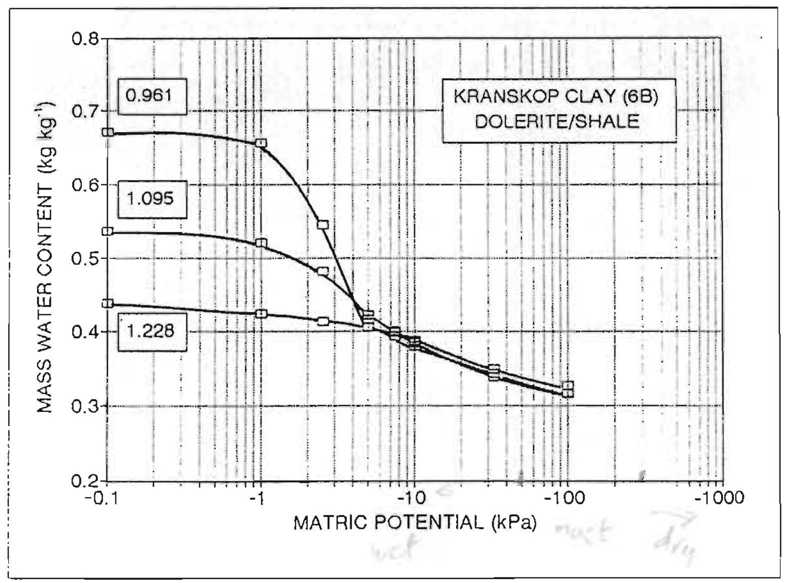
APPENDIX 7

Water retentivity curves at a range of bulk densities for selected forestry soils.

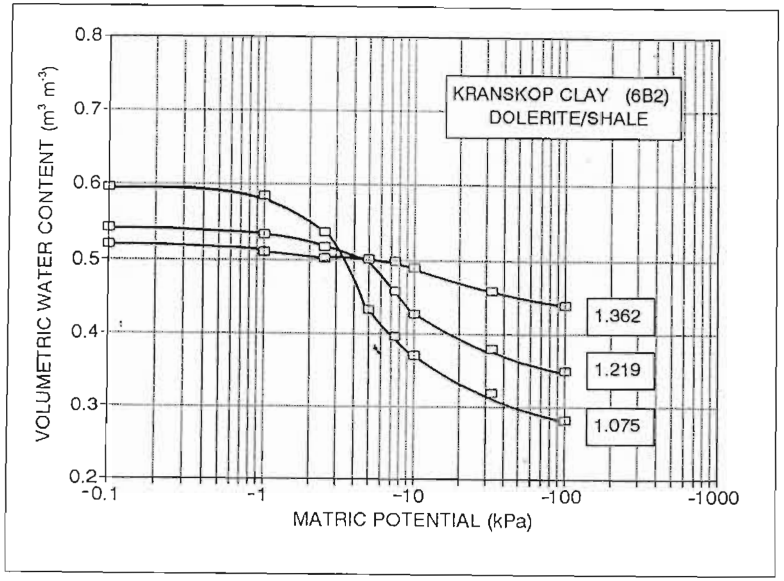

CARTREF SANDY LOAM (2E)
NATAL GROUP SANDSTONE
1.442
1.642
1.834
VOLUMETRIC WATER CONTENT (m³ m⁻³)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1
-10
-100
-1000
MATRIC POTENTIAL (kPa)


KRANSKOP CLAY (6B)
DOLERITE/SHALE
1.228
1.095
0.961
VOLUMETRIC WATER CONTENT (m³ m⁻³)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
10
100
1000
MATRIC POTENTIAL (kPa)

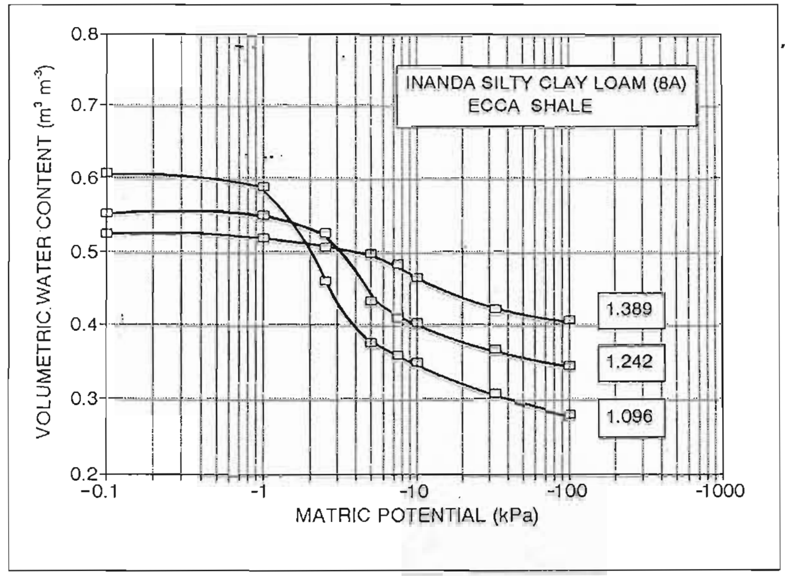

CARTREF SANDY LOAM (2 E)
NATAL GROUP SANDSTONE
1.442
1.642
1.834
MASS WATER CONTENT (kg kg⁻¹)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1
-10
-100
-1000
MATRIC POTENTIAL (kPa)


KRANSKOP CLAY (6B)
DOLERITE/SHALE
0.961
1.095
1.228
MASS WATER CONTENT (kg kg⁻¹)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
-1
-10
-100
-1000
MATRIC POTENTIAL (kPa)

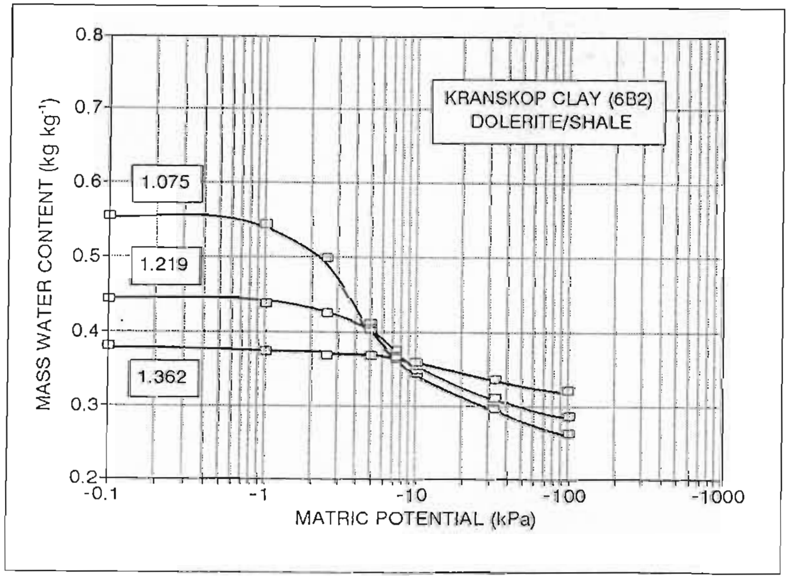
Appendix 7:



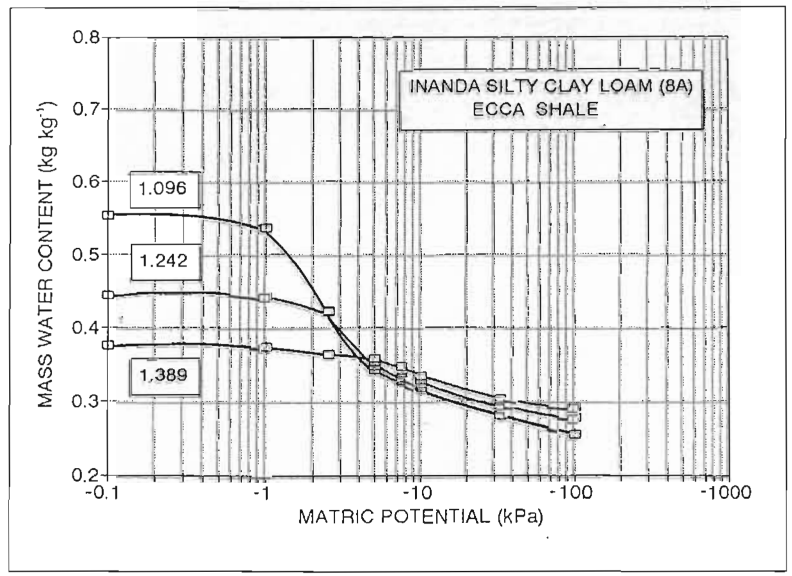
KRANSKOP CLAY (6B2)
DOLERITE/SHALE
VOLUMETRIC WATER CONTENT (m³ m⁻³)
MATRIC POTENTIAL (kPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
-1
-10
-100
-1000
1.362
1.219
1.075



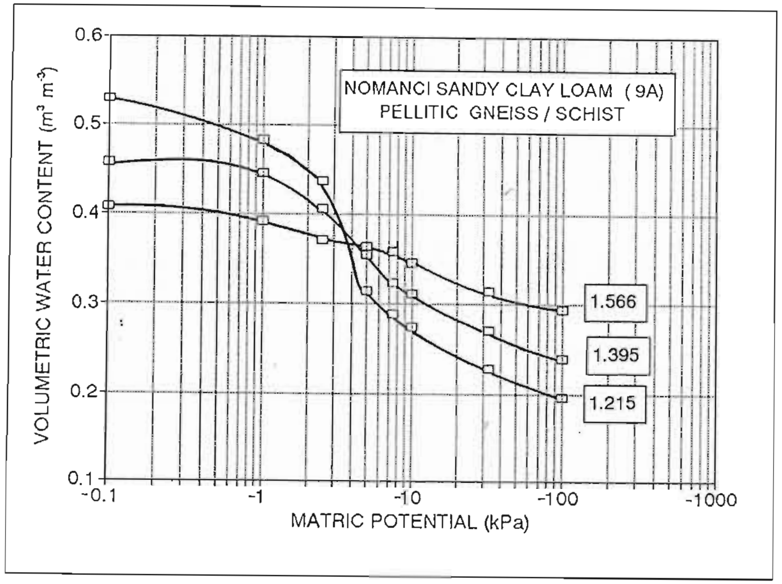
INANDA SILTY CLAY LOAM (8A)
ECCA SHALE
VOLUMETRIC WATER CONTENT (m³ m⁻³)
MATRIC POTENTIAL (kPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
-1
-10
-100
-1000
1.389
1.242
1.096

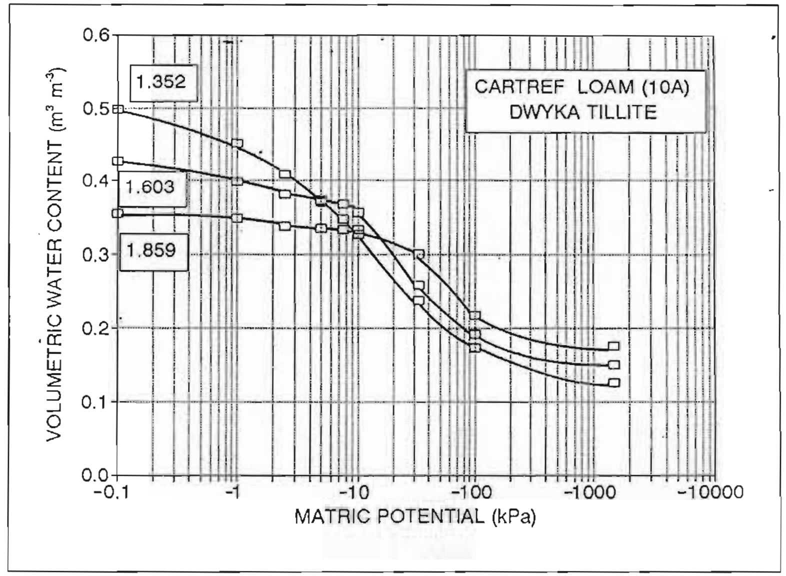


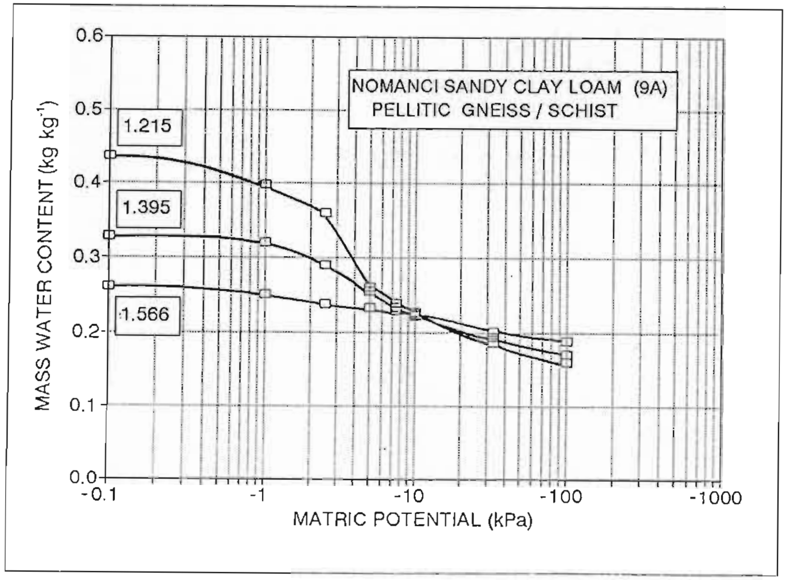
KRANSKOP CLAY (6B2)
DOLERITE/SHALE
MASS WATER CONTENT (kg kg⁻¹)
MATRIC POTENTIAL (kPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
-1
-10
-100
-1000
1.075
1.219
1.362

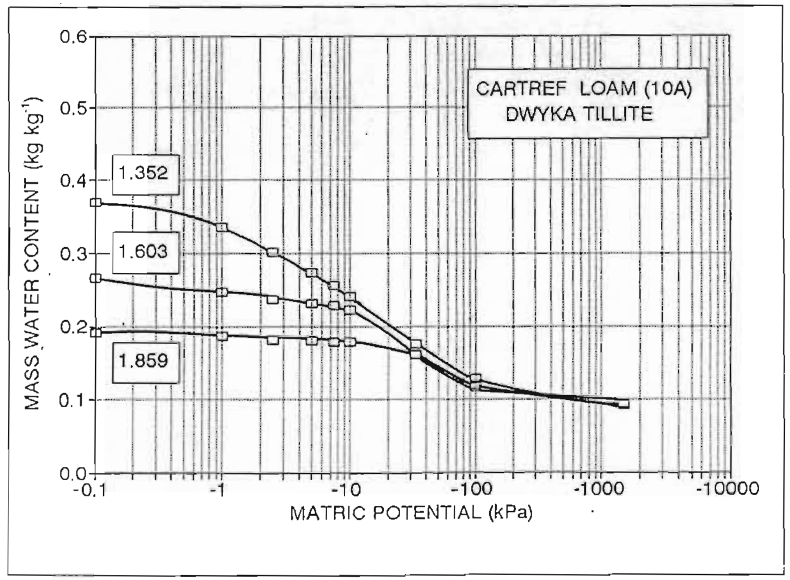


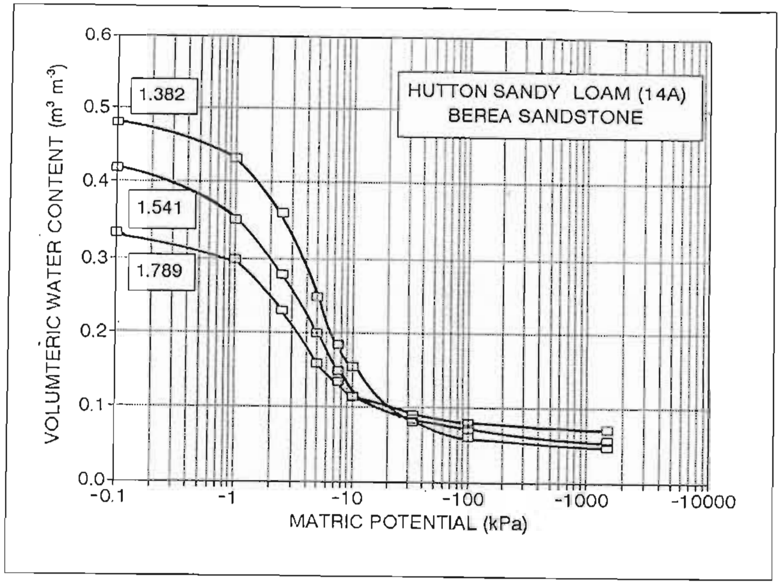
INANDA SILTY CLAY LOAM (8A)
ECCA SHALE
MASS WATER CONTENT (kg kg⁻¹)
MATRIC POTENTIAL (kPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-0.1
-1
-10
-100
-1000
1.096
1.242
1.389

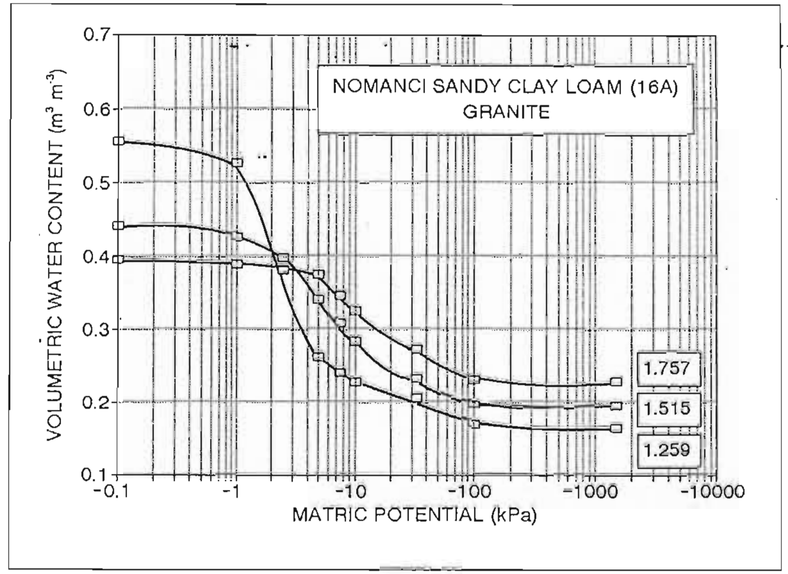

NOMANCI SANDY CLAY LOAM (9A)
PELLITIC GNEISS / SCHIST
VOLUMETRIC WATER CONTENT ($m^3 m^{-3}$)
MATRIC POTENTIAL (kPa)
0.6
0.5
0.4
0.3
0.2
0.1
-0.1
-1
-10
-100
-1000
1.566
1.395
1.215

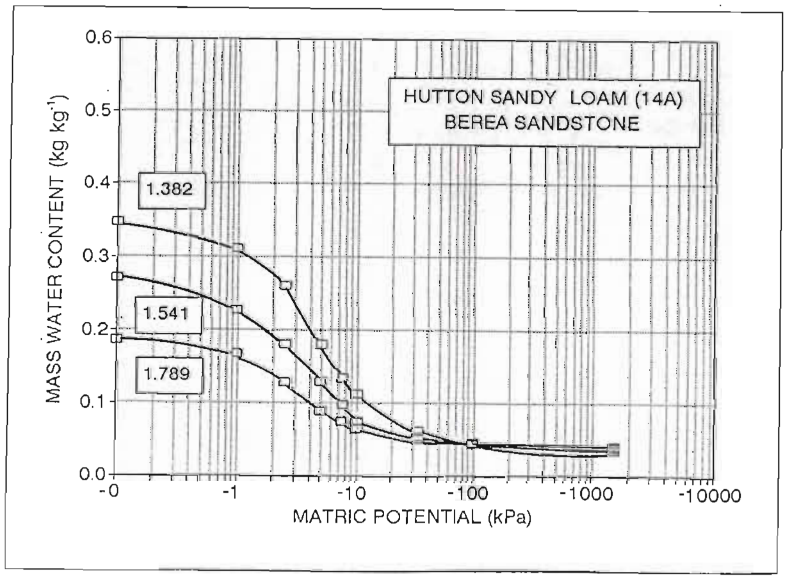

CARTREF LOAM (10A)
DWYKA TILLITE
VOLUMETRIC WATER CONTENT ($m^3 m^{-3}$)
MATRIC POTENTIAL (kPa)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1
-10
-100
-1000
-10000
1.352
1.603
1.859

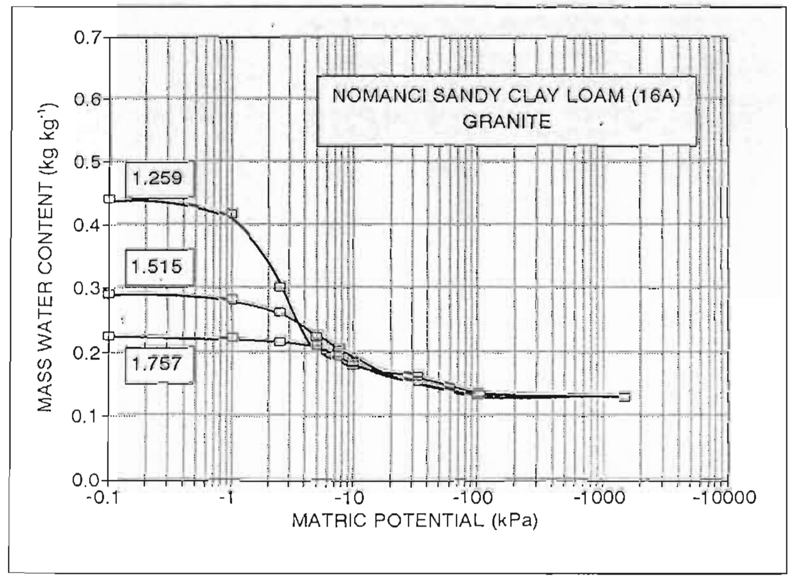

NOMANCI SANDY CLAY LOAM (9A)
PELLITIC GNEISS / SCHIST
MASS WATER CONTENT ($kg kg^{-1}$)
MATRIC POTENTIAL (kPa)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1
-10
-100
-1000
1.215
1.395
1.566

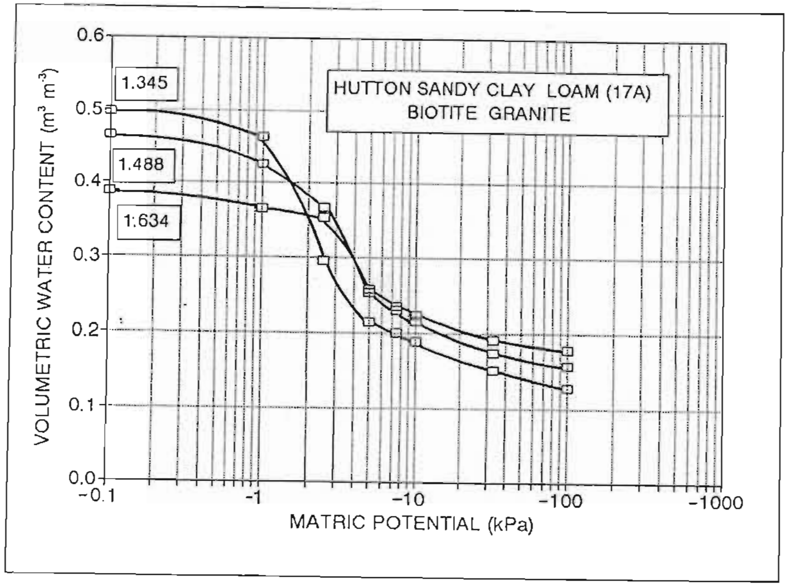

CARTREF LOAM (10A)
DWYKA TILLITE
MASS WATER CONTENT ($kg kg^{-1}$)
MATRIC POTENTIAL (kPa)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1
-10
-100
-1000
-10000
1.352
1.603
1.859

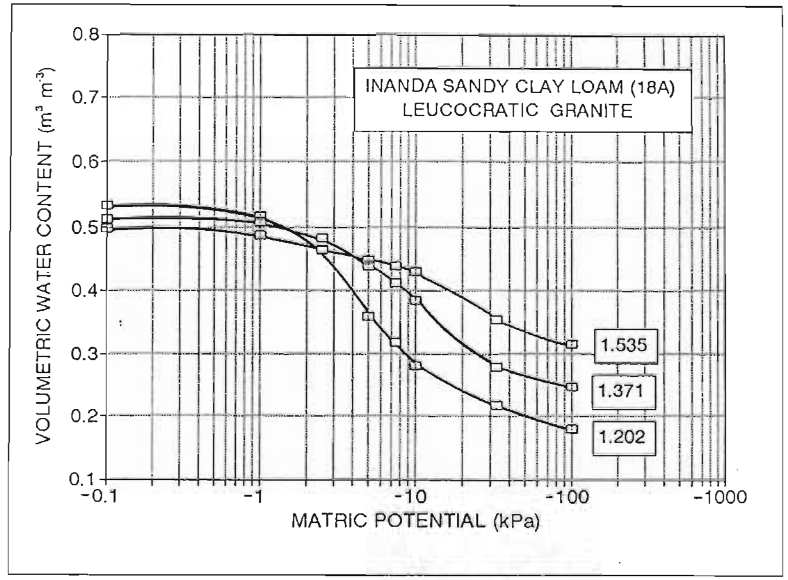

HUTTON SANDY LOAM (14A)
BEREA SANDSTONE
VOLUMTERIC WATER CONTENT (m³ m⁻³)
MATRIC POTENTIAL (kPa)
1.382
1.541
1.789
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-0.1
-1
-10
-100
-1000
-10000

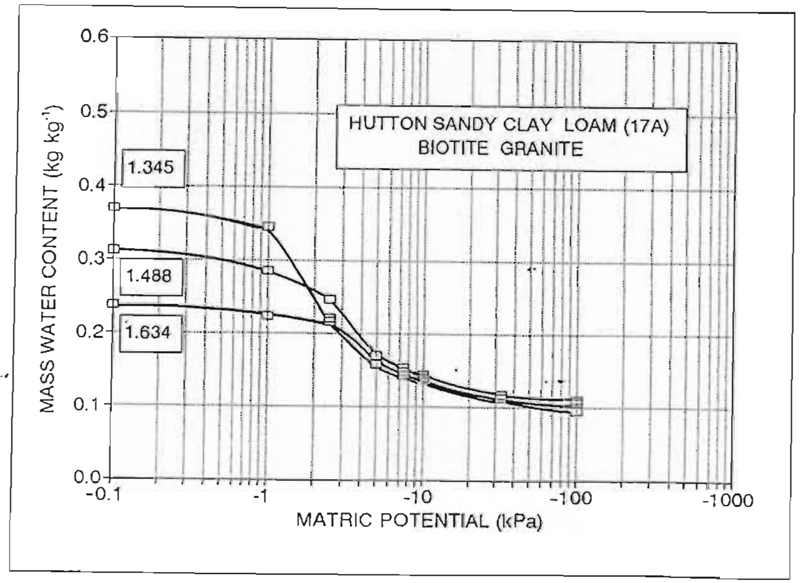

NOMANCI SANDY CLAY LOAM (16A)
GRANITE
VOLUMETRIC WATER CONTENT (m³ m⁻³)
MATRIC POTENTIAL (kPa)
1.757
1.515
1.259
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-0.1
-1
-10
-100
-1000
-10000

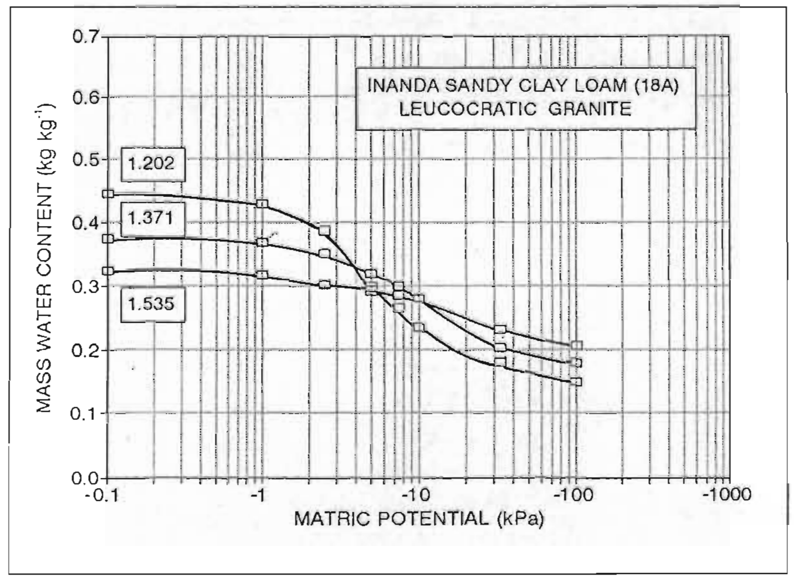

HUTTON SANDY LOAM (14A)
BEREA SANDSTONE
MASS WATER CONTENT (kg kg⁻¹)
MATRIC POTENTIAL (kPa)
1.382
1.541
1.789
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-0
-1
-10
-100
-1000
-10000


NOMANCI SANDY CLAY LOAM (16A)
GRANITE
MASS WATER CONTENT (kg kg⁻¹)
MATRIC POTENTIAL (kPa)
1.259
1.515
1.757
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-0.1
-1
-10
-100
-1000
-10000


HUTTON SANDY CLAY LOAM (17A)
BIOTITE GRANITE
VOLUMETRIC WATER CONTENT (m^3 m^{-3})
MATRIC POTENTIAL (kPa)
1.345
1.488
1.634
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-0.1
-1
-10
-100
-1000


INANDA SANDY CLAY LOAM (18A)
LEUCOCRATIC GRANITE
VOLUMETRIC WATER CONTENT (m^3 m^{-3})
MATRIC POTENTIAL (kPa)
1.535
1.371
1.202
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
-0.1
-1
-10
-100
-1000


HUTTON SANDY CLAY LOAM (17A)
BIOTITE GRANITE
MASS WATER CONTENT (kg kg^{-1})
MATRIC POTENTIAL (kPa)
1.345
1.488
1.634
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-0.1
-1
-10
-100
-1000


INANDA SANDY CLAY LOAM (18A)
LEUCOCRATIC GRANITE
MASS WATER CONTENT (kg kg^{-1})
MATRIC POTENTIAL (kPa)
1.202
1.371
1.535
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-0.1
-1
-10
-100
-1000

Appendix 7: (continued)