THE COMPACTION SUSCEPTIBILITY OF SOILS IN THE FREE STATE

by

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DECLARATION

I hereby declare that this thesis, prepared for the degree Magister Scientiae Agriculturae, which was submitted by me to the University of the Orange Free State, is my own work and has not been submitted to any other university.

I also agree that the University of the Orange Free State has the sole right to publication of this thesis.

Signed: 

Alfredo Bernardino Julio da Costa Nhantumbo

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INTRODUCTION

1.1 An overview

The diminishing land resources associated with the increasing demand for food (Raghavan, Alvo & McKyes, 1990) and diminishing financial profits (Boone, 1986 and Chamen, Vermeulen, Campbell & Sommer, 1992), have put pressure on science and technology to increase the productivity of the existing agricultural soils and efficiency of agricultural production. For this reason, farmers have been practising frequent rotations and heavily mechanised cropping systems which is characterised by an increased number of passes of machines carrying heavy loads in their wheels. In the tropics particularly, new lands are being brought into cultivation (Gupta & Allmaras 1987).

The increase in traffic and weight of agricultural machinery has increased the danger of soil compaction and its detrimental effect on crop production. This phenomenon is also a big concern in commercial forestry production (Sands, Greacen & Gerard, 1979 and Smith, 1995). In a marine clay soil district of The Netherlands, a result of a survey by Boone (1986) revealed that only a small part of the field remains untouched by wheels whereas the greater part is compacted more than once, even up to eight times, by agricultural implements. Lately, according to Voorhees (1992) a review by Hakansson *et al.* (1988) revealed that in a modernised farming system with semi-random traffic patterns, the total area of a field covered in one season by rear tractor wheels alone, is about twice the total field area when harvest wheel traffic is included. The increase in the axle load of agricultural machines is a cause of concern. McKibben (1971) stated that in a period of twenty years, between 1948 and 1968, the average mass of tractors increased from 2.7 to 4.5 tons. Similarly, Gupta & Allmaras (1987) pointed out that by the 80's the average mass of agricultural machines was 6.8 tons, with larger units weighting more than 22.4 tons.

Soil compaction refers to the compression of unsaturated soil, during which there is a decrease in volume for a given mass of soil and the bulk density of the body increases accompanied by a simultaneous reduction in fractional air volume (Bodman & Constantin 1965; McKibben, 1971 and Gupta, Sharma & Defranchi, 1989). The process by which a soil volume is decreased due to an external force is called compression and the ease with which compression can occur is soil compressibility. The maximum bulk density to which a soil can be packed by a given amount of energy is called compactibility (Bradford & Gupta, 1986).

At low compression pressures, the bulk density is low and determined by the size distribution, shape and specific density of the particles (Larson, Gupta & Useche, 1980). If the compression increases, the bulk density will increase up to a maximum. This relationship can be shown by the Figure 1.1. In this theoretical compression curve the $\log_{10}$ of applied pressure versus bulk density relationship is plotted. The straight portion of the curve is called virgin compression curve (VCC). The slope of the VCC is the compression index.

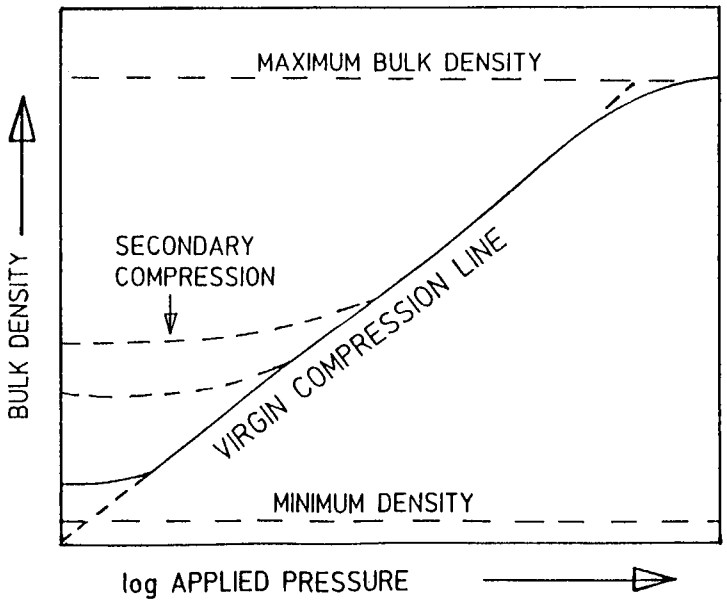


Figure 1.1 Theoretical compression curve (Smith, 1995).

Soil compaction is not always harmful. There are times where seedbed compaction is done using rollers or pressure wheels to ensure adequate soil-seed contact. To distinguish between harmful and desired compaction, Gupta & Allmaras (1987) proposed the term excessive compaction.

Excessive compaction of agricultural soils is one of the main causes of soil degradation. According to Boone (1986) it started to draw the attention of agricultural scientists and farmers only from the 70's. Degradation processes, of which soil erosion is the most pronounced, affect agricultural soils throughout the world. Lal & Stewart (1990) cited UNEP (1982) which estimated that over millennia as much as two billion hectares of land, that were once biologically productive, have been rendered unproductive through soil degradation. The same authors have referred to a FAO/UNEP (1983) report which showed that the degradation rate is estimated at five to seven million hectares per year and the annual rate may raise to ten million hectares by the turn of the century. For the South African situation, it is estimated that approximately 1.5 million ha of cultivated land is susceptible to soil compaction of which the majority is in the Free State Province (Bennie, 1998).

Soil degradation leads to political and social instability. It affects also the economic structure of several countries (Taylor, 1992). The economic impact of soil compaction is difficult to asses due to the vast number of interrelated factors involved, consequently quantitative information is insufficient to permit a cost/benefit analysis, but it is well known that corrective measures to alleviate compaction may incur high costs. Gill (1971) estimated that around $1.2 billion were being lost annually only in the United States of America resulting from decreased yields and increased energy costs during field tillage. Similarly in Quebec (Canada) estimated costs of soil compaction vary from 30 to 100 million US dollars for the same period (Angers, 1990).

Induced compaction can cause long-lasting changes in the physical and chemical properties and biological activities in the soil environment. Consequently, a decline in

soil productivity may arise due to a concentration of electrolytes and toxic chemicals (Lal & Stewart, 1990) changes in availability of nutrients and in soil structure.

Soil structure is the arrangement of primary soil particles into secondary particles or aggregates (Gupta *et al.*, 1989). This arrangement can be seriously affected by compaction. Rusanov (1991) referred to Kachinsky (1927) and Pigulevsky (1929) who stated that tractors of 2-6 t showed a substantial deterioration of soil characteristics including its structure which can require 15 years or more for self restoration. This is a serious problem because mechanical alleviating procedures such as subsoiling represent costs over and above normal tillage (Bennie & Krynauw, 1985 and Raghavan *et al.*, 1990). Sometimes, the effects can be removed only at high costs which cannot be paid by normal agricultural exploitation (Boone, 1986).

Soil compaction is normally caused by loads exerted by agricultural equipment but it may also result from factors other than surface applied stress (Hadas, 1994). The causes of soil compaction can be divided into external and internal factors. The main external factor is the compactive effort of downward forces applied by machines which are usually of short duration in the case of moving vehicles. The impact of raindrops can also result in soil compaction (McKyes, 1985 and Hodara & Slowinska-Jurkiewicz, 1993). The internal factors influencing the compactibility of soils include organic matter content, the nature of the clay fraction (Harris, 1971), particle size distribution and water content (Bennie & Krynauw, 1985 and Hamdani, 1983). The behaviour of soils under external forces is completely dependent on the relationship between the above mentioned internal factors (Larson *et al.*, 1980; Hamdani, 1983; Smith, 1995 and Da Silva, Kay & Perfect, 1997).

The compaction process leads to a densification of soils as a result of the application of stresses, usually of short duration (Soane, 1990). The stress can be caused by rolling, tramping or vibration (Bradford & Gupta, 1986) resulting in air expulsion (Smith, 1995). According to Bradford & Gupta (1986), this phenomenon is typical during the traffic of animals and agricultural equipment.

Cohron (1971) and Soane, Blackwell, Dickson & Painter (1981) stated that increased mechanisation of crop production have led to increased application of the external forces to top soils where permanent strains and failures result in compaction. The strain and failure may be a consequence of breakage of stable bonds formed during natural aggregation (Gupta *et al.*, 1989). The depth of maximum compaction caused by lighter vehicles is in the topsoil (0 to 300 mm) while heavy equipment tends to compact the subsoil, generally in the depth of 300 to 600 mm (Raghavan *et al.*, 1990 and Voorhees, 1992). The structure of an unstable soil can be destroyed to a depth of 1m in extreme cases (Boone, 1986). Gameda, Raghavan, McKyes & Theriault (1987b) found in research conducted on a clay soil that equipment with 10 and 20 tons axle loads increased subsoil bulk densities. The collective data from studies of several researchers showed that wheel traffic from machinery with axle loads in excess of 10 tons can cause increases in bulk density and penetrometer resistance deeper than 300 mm (Voorhees, 1992).

According to Bodman & Constantin (1965) compaction may occur in soils of different texture but certain soil texture types are more vulnerable to excessive compaction than others, especially well-sorted fine sandy loams and loamy fine sands with a high fine sand fraction and low carbon content (Bennie & Krynauw, 1985). Sandy soils with well-sorted particle size distributions and low cohesion compact and consolidate easily under pressure (Bennie & Botha, 1986).

The clay mineralogy is one of the internal factors that affect the soil behaviour according to the type of chemical elements involved. Gerard (1965) concluded that slow drying of soil containing primarily silt and clay saturated with the divalent ions, Ca^{2+} and Mg^{2+}, increased the strength possibly by causing better distribution, or orientation of soil particles. Rapid drying produced briquettes of much lower maximum strength, probably due to the flocculating action of the ions and the disruptive action of the rapidly escaping water molecules.

The water content of the soil is another very important internal factor affecting the compactibility of soils (Bingner & Wells, 1992). During the compaction process using

the Proctor test procedure, there is a water content where the soil is susceptible to produce the maximum bulk density (Figure 1.2). This water content is commonly called "optimum water content". Smith (1995) and Etana *et al* (1997) have suggested the term "critical water content". Saini, Chow & Ghanen (1984) felt that "optimum water content" has an engineering connotation while for Etana, Comia & Hakansson (1997) the term "critical water content" is more appropriate as it reflects the negative effect of soil compaction on arable land. The theoretical relationship between the water content and the maximum bulk density is shown in the Figure 1.2.

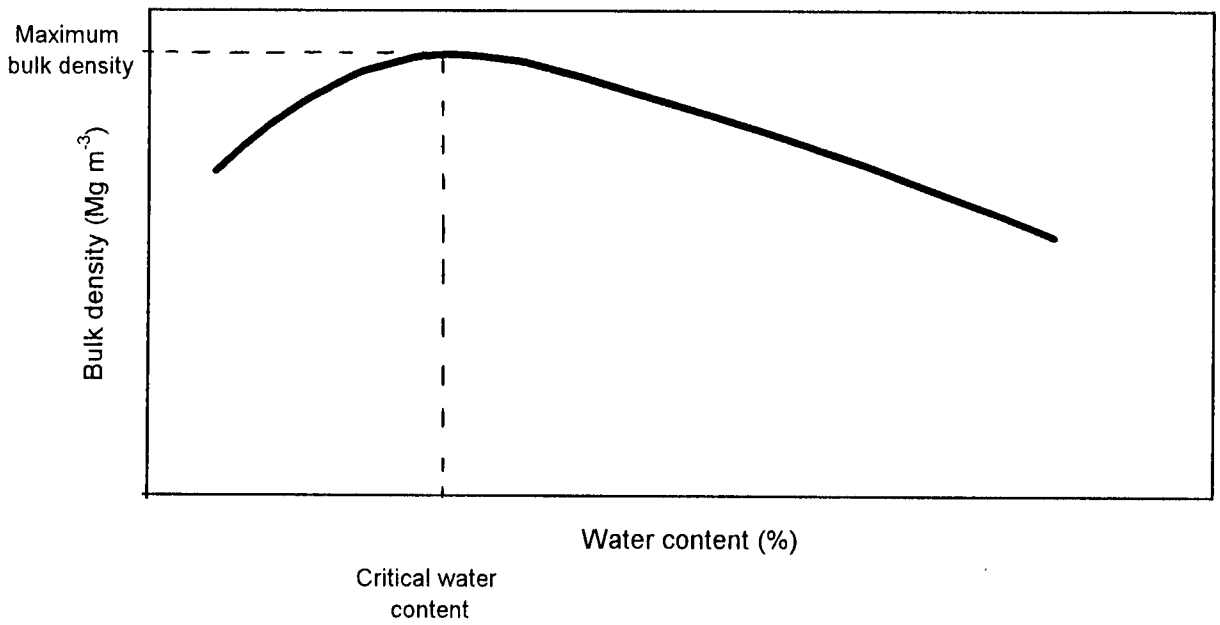


Figure 1.2 Theoretical curve of bulk density as function of water content.

McKyes (1985), has stated that densification of soil can be up to five times as severe at the critical water content for a given compacting pressure compared to dry soil. He argued that the ease of compaction of soils increases with wetting because of decreasing cohesion forces and friction angles. For example, Gupta *et al.*, (1989) found that an air dry soil compacted at an applied stress of 173 kPa reached a similar bulk density as a soil compacted at field capacity at an applied stress of 87 kPa. However, soils compacted at a constant water content will have higher strengths at higher bulk densities, which can be ascribed to the packing phenomenon of the particles. This was defined by Gupta &

Larson (1979) as an entrapment of certain particles in the void spaces of packing assemblages formed by other particles of larger diameter.

The critical water content is strongly influenced by organic matter content and it will increase with increasing organic matter content because organic material increases the consistency limits of the soil. Increasing organic matter content will increase soil strength at high water contents but will decrease it in drying soils (Ekwe & Stone, 1995). Thus, it increases the range of soil water contents at which farm machines can operate without increasing soil strength excessively (O'sullivan, 1992).

Organic matter plays an important role in soil physical behaviour. Under cooler climatic conditions, where soils have a higher organic matter contents and a more stable structure, root growth restrictions under field conditions are not as commonly observed and are less easily related to yield responses (Voorhees, 1992). Etana *et al.*, (1997) and Da Silva *et al.*, (1997) found that bulk density decreased with increasing organic matter content. This negative relationship is widely recognised (Spivey, Busscher & Campbell, 1986; Soane, 1990; Wagner, Ambe & Ding, 1984 and Sands *et al.*, 1979). The organic matter content can also decrease the compressibility of soils (Guerif, 1990). It forms a structural framework (Gosselink, Hatton & Hopkinson 1984; Guerif, 1990), and increases the shear strength of the soils as it improves aggregate stability by decreasing the hydration of soil aggregates by water (Ekwe & Stone, 1995). However, not all organic material improves soil aggregate stability. For instance, according to Ekwue (1990), MacRae & Mehuys (1985) found that peat has only diluting effects on the bulk density but does not affect physical behaviour of the soils.

The use of deep conventional tillage for alleviating topsoil compaction is generally accepted whereas the effectiveness of methods and processes that reduce subsoil compaction is not well defined. Gameda *et al.*, (1987b) cited Dumas *et al.*, (1975) and Negi *et al.*, (1980) who noted that some researchers have observed that subsoiling reduces soil compaction and results in higher yields. The beneficial effects of deep

loosening can easily be cancelled by subsequent tillage operations (Fortune & Burke, 1987).

Examination of the soil matrix of a compacted soil reveals a reduction in size and number of macropores and a change of shape and continuity of pores (Bennie & Krynauw, 1985). This change generally affects the soil water retention characteristics, reducing the conductivity, permeability and diffusivity of water and air through the soil-pore system (Hadas, 1994). Consequently, the crops are more susceptible to water and nutrient stress during the growing season. The internal drainage of the soil will also be slowed, which leads more readily to high degrees of saturation during rainy periods of the year, and insufficient aeration (McKyes, 1985). Since wheel traffic is normally not uniformly distributed over the entire field surface, non-uniform water movement and/or water use can be expected (Voorhees, 1992).

When compaction occurs most of the physical soil properties change. The change in soil compaction can be described in terms of measured bulk density, void ratio, or total porosity, parameters which indirectly refer to soil structure. Another parameter which is widely used is the penetrometer resistance.

Penetrometer resistance measures the mechanical resistance of the soil which refers to the difficulty that a root encounters in growing into the soil matrix or the difficulty a seedling encounters in emerging through the soil surface (Letey, 1985). Penetrometer resistance, the reading from a penetrometer that measures the pressure required to force a steel probe into the soil, is a commonly accepted technique to predict the mechanical impedance experienced by a root during its elongation through the soil (Raghavan *et al.*, 1990 and Bennie, 1991).

For a specific soil, penetrometer resistance is directly correlated with bulk density when measurements are taken at the same water content (Bennie & Botha, 1986). Specific penetration resistance values have proven to be valuable empirical tools in specific experiments but are invalidated for general application in other experiments under

different experimental conditions because no universal factor is found up till now can be explained by considering the complex system of functional relationships between soil compaction and root crop growth (Boone, 1986). For instance, plant roots growing through an apedal soil, elongate by exerting pressure on and displacing soil particles at the root tip. While according to Hakansson (1982) as cited by Gameda *et al.*, (1987a), in a structured soil, they grow through the network of cracks, earthworm holes although the structured soil may exhibit a very high penetrometer resistance.

Increasing bulk density due to compaction results in decreasing total porosity and macropores and an increase in micro-capillary porosity (Bennie & Krynauw, 1985). This leads to a reduction in soil water conductivity in the soil water range wetter than field water capacity and an increase in soil water conductivity in drier soils (Gameda *et al.*, 1987b). This difference is attributed to the fact that uncompacted soils have high evaporative losses whereas highly compacted ones hold water tightly in small pores (Raghavan *et al.*, 1990).

In many cases, tillage in the semi-arid regions of Southern Africa are being performed in well-rounded and sorted fine sandy soils of aeolian origin (Bennie & Botha, 1986) as is generally the case for the soils in the Free State. The fine sandy apedal soils, of which large areas are cropped in South Africa, are very susceptible to compaction when cultivated (Bennie & Van Antwerpen, 1988).

The apedal fine sandy soils are often grouped among those of the highest land use capability as they drain quickly and can be cultivated and tracked soon after heavy rainfall, but their packing characteristics can present management problems (Panayiotopoulos & Mullins, 1985). According to Panayiotopoulos & Mullins (1985), Harrold (1975) stated that structureless soils can compact easily when in a wet state and become dense enough to inhibit root growth whilst in other cases it forms too loose a seedbed which is vulnerable to wind erosion and gives poor seed-soil contact.

In agricultural soil studies, the shear strength of soils is important for describing their susceptibility to applied pressures from farm machinery and implements (Ohu, Raghavan, McKyes & Mehuys, 1986). It is also important in determining the specification of cultivation machines designed to change the soil structure for improved agricultural production.

Identification of the 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 (Smith, Johnston & Lorentz, 1997c). Many research workers have reported that a decrease in root penetration was associated with an increase in soil bulk density (Taylor & Gardner, 1963). To gain a better understanding of the harmful effect of compaction on plant growth, the contribution of relative bulk density and compactive effort have to be evaluated (Smith, 1995).

The state or degree of compaction of soils has received much attention, but what may appear to be simple process is actually difficult to predict and describe for several reasons. These include highly complex character of the process, a wide variability of soil properties, and the nature of the applied forces acting on soils (Larson *et al.*, 1990). Bennie & Van Antwerpen (1988) proposed a classification of compaction degree for agricultural soils into four (4) classes ranging from low to a high degree of compaction when evaluating an empirical model for the root impeding characteristics of compacted soil layers. This classification is based only on bulk density. Similarly, Smith (1995) assessing compaction susceptibility of South African forestry soils, proposed five (5) classes based on maximum bulk density and compression index.

Because of the difficulty and cost of subsoil cultivation, it appears likely that more importance will be attached to the avoidance of subsoil compaction since there is wide spread evidence that such compaction may persist for many years (Soane, Dickson & Campbell, 1982). The identification of factors affecting strength development is important for evaluating the effects of compaction on soil properties and tree growth, soil trafficability and timing of tillage operations (Smith *et al.*, 1997c).

1.2 Background of the study

There is general agreement that soil compaction is one of the main causes for soil degradation and it is harmful for plant growth and consequently it seriously affects the crop yields, the economy as well as the environment. The questions which can arise from this statement are:

- To what extent is a soil compacted, and how can we determine the degree of compaction?

- How can we determine that a certain soil is more susceptible to compaction than another?

These questions can be answered if we can precisely define critical limits of the soil properties beyond which crop growth will be impeded. These limits vary among soils, climatic conditions, land use, farming systems, plant species, and agro-ecological environments.

Gupta & Allmaras (1987) stated that simple guidelines should be developed for extension specialists and farmers. These guidelines should include a range of applied pressures and soil water contents that lead to excessive compaction; the soil types and areas that are susceptible to excessive compaction; and plant growth limiting conditions in a given area. Additionally, computer models could be used to evaluate management systems that may prevent or alleviate excessive compaction.

Much research has been done towards defining critical values for certain compaction parameters based on the intrinsic soil properties. The parameters usually used are penetrometer resistance, compression index and relative bulk density (also called relative compaction or degree of compactness).

Reports from different authors, stated that penetrometer resistance values varying between 1.2 and 2 MPa will be harmful for plant root growth and consequently to the crop yield. Increasing compression index values, are normally associated with higher soil compaction susceptibility. The procedure for the determination of penetrometer resistance and compression index is standardised. The determination of relative bulk density is still not standardised. Different researchers have produced a number of proposals.

All researches regarding the definition of relative bulk density, are based on the concept stated by Da Silva *et al.* (1974) citing Erikson *et al.* (1974) where relative compaction is defined as the ratio between the actual bulk density and a reference bulk density value. Basically three proposals were produced for the definition of reference bulk density. For Hakansson (1990), the reference value is the bulk density obtained by a standardised laboratory test under uniaxial stress of 200 kPa. Others consider the maximum bulk density, obtained through the standard Proctor test as reference value. Bennie & Van Antwerpen (1988) proposed another approach according to which the relative bulk density of a specific soil can be calculated using Equation (1.1).

$$RD = \frac{BD - BD_{min}}{BD_{max} - BD_{min}} \qquad (1.1)$$

Where: RD - relative density also called relative compaction or degree of compactness (unitless)

BD_{min} - minimum bulk density (Mg m^{-3})

BD_{max} - maximum bulk density (Mg m^{-3})

This proposal is based on the concept that the bulk density of a certain soil varies from a minimum to a maximum value and the minimum value is a certain value larger than zero. Thus, a standard procedure will have to be developed for the determination of the

minimum bulk density of soils. Panayiotopoulos & Mullins (1985) have proposed a procedure for the determination of the bulk density of soils in a loose state which they called the "loose bulk density".

There is a general consensus that a good relationship exists between penetrometer resistance and the degree of compactness. Therefore, a good relationship between the relative density (RD) as defined by Bennie & Van Antwerpen (1988) and penetrometer resistance should also exist if this equation is valid. Consequently, critical relative bulk density values for each kind of soil should be determined. This will make it possible to classify the soils according to their degree of compaction. Bennie & Van Antwerpen (1988) proposed the following relative bulk density threshold values for agricultural soils:

RD < 0.5 – low degree of compactness
0.5 < RD < 0.6 – medium degree of compactness
0.6 < RD < 0.7 – high degree of compactness
RD > 0.7 – very high degree of compactness

Smith *et al.*, (1997b) classified the compaction susceptibility for forestry soils based on the maximum bulk density and maximum compression index, in five classes.

From this discussion it is evident that there is a need for determining the relationship between the different intrinsic soil properties and the parameters for evaluating the degree of compactibility of soils. This will allow technical staff to be able to predict the susceptibility of agricultural soils to compaction from easily measured properties.

1.3 Objectives of the study

This study was conducted using soils from different parts of Free State namely Bainsvlei, De Brug, Glen, Hoopstad, Ladybrand and Tweespruit which represented a wide range of soil properties. The soils were submitted to the determination of particle size distribution,

organic matter content, maximum and minimum bulk densities, compression index, optimum water content for compaction and penetrometer resistance.

To derive a procedure for the prediction of the compaction characteristics of the soils in the Free State, five main objectives were highlighted:

- To determine the maximum and the minimum densities of the soils and the properties affecting them.

- To investigate the applicability of the relative bulk density concept.

- To determine the compressibility of soils and the soil properties affecting it.

- To propose a procedure for the prediction and classification of the compactibility of the Free State soils.

- To compare the results from this investigation on semi-arid agricultural soils with those obtained by Smith (1995) for forestry soils from more humid climatic regions with possibly different clay mineralogy and higher organic matter contents.

CHAPTER 2
MATERIAL AND METHODS

Samples from a variety of soils were collected for the determination of the maximum and minimum bulk densities as well as the compression indices and penetrometer resistance. The values of these compaction and compactibility variables will be related to intrinsic soil properties to obtain empirical prediction functions. The different intrinsic soil properties that will be considered are texture, organic matter content and gravimetric water content.

2.1 Soils

The soils were collected within a 150 km radius from Bloemfontein in a semi-arid climate with an average rainfall varying between 500-560mm (Department of Environment Affairs, 1986). The soils collected from Bainsvlei and Hoopstad were developed from wind blown-deposits (aeolian) while soils collected from De Brug, Tweespruit and Ladybrand originated mainly from colluvial material that moved down slopes under gravitational forces, with the aid of water.

Care was taken to select soils covering a wide range of silt plus clay and organic matter contents. Twenty two (22) samples of about 120 kg each varying from very loose to highly structured soils were collected. The samples represent a broad range of soils used for agricultural purposes in the Free State Province varying in texture from sandy to clay soils. The soils were classified according to the South African Soil Classification System (Soil Classification Working Group, 1991) and Soil Taxonomy (Soil Survey Staff, 1992). The locality of the sites and the soil classification are given in the Table 2.1.

During the collection, the soils were being coded in three letters according to the following procedure: the first letter represents the locality; the second letter is the number of the profile in the locality and the last letter is an indicator of the horizon.

Table 2.1: Coding and classification of the soils

Locality	Code	Soil Classification		
		South African System		Soil Taxonomy
		Soil form	Family	
BLOEMFONTEIN	B1A	Bainsvlei	Amalia	Ustic Quartzipsaments
	B2A	Hutton	Stella	Ustic Quartzipsaments
	B1B	Bainsvlei	Amalia	Ustic Quartzipsaments
	B3A	Valsrivier	Luckhoff	Typic Haplustalfs
DE BRUG	D2B	Hutton	Stella	Ustic Quartzipsaments
	D3A	Valsrivier	Luckhoff	Typic Haplustalfs
	D1B	Valsrivier	Luckhoff	Typic Haplustalfs
	D1A	Valsrivier	Luckhoff	Typic Haplustalfs
GLEN	G1A	Bonheim	Mkuze	Aridic Haplusterts
HOOPSTAD	H5A	Clovelly	Setlagole	Ustic Quartzipsaments
	H2A	Clovelly	Setlagole	Ustic Quartzipsaments
	H4A	Avalon	Kameelbos	Ustic Quartzipsaments
	H3A	Clovelly	Mooilaagte	Ustic Quartzipsaments
	H1A	Hutton	Stella	Ustic Quartzipsaments
	H1B	Hutton	Stella	Ustic Quartzipsaments
LADYBRAND	L3A	Avalon	Mafikeng	Ustic Quartzipsaments
	L2B	Clovelly	Mooilaagte	Ustic Quartzipsaments
	L1A	Clovelly	Mooilaagte	Ustic Quartzipsaments
	L3B	Avalon	Mafikeng	Typic Plinthustalfs
	L1B	Avalon	Mooilaagte	Ustic Quartzipsaments
TWEESPRUIT	T2A	Westleigh	Mareetsane	Typic Plinthustalfs
	T1A	Swartland	Adelaide	Typic Haplustalfs

Before any determinations were performed, the samples were air dried, the clods were broken up gently (if necessary) to pass through a 6 mm sieve, similarly to the procedure followed by Angers (1990) and Morgan *et al.*, (1993). Another aim of sieving was to separate the root material from the soil.

2.2 Particle size distribution

The particle size distribution was measured by the pipette method using a 50g sample of the soil passed through a 2 mm sieve and dispersed using sodium hexametaphosphate. The sand fraction was separated from the silt plus clay by passing the sample through a 0.053 mm sieve. The silt and the clay contents were determined using a pipette following the instructions described by The Non-Affiliated Soil Analysis Work Committee (1990).

For the purpose of this study the following particle size classes were separated and expressed as a percentage of the total sample: < 0.002mm (clay), 0.002 to 0.02mm (fine silt), 0.02 to 0.053mm (coarse silt), 0.053 to 2.00mm (sand) and <0.053mm (silt plus clay, S+C).

2.3 Bulk density

2.3.1 Maximum bulk density and critical water content

The maximum bulk density of each soil was determined using the standard Proctor high density compaction ASTM method as described by Felt (1965).

Sub-samples weighing 2500g of air-dried soil, which was passed through a 6 mm sieve, were placed into plastic bags and water was added to obtain a range of water contents. The bags were sealed to avoid evaporation and immediately shaken thoroughly for a period of 3 minutes. The shaking was repeated twice a day and the small aggregates that formed were crushed by hand. All the samples were allowed to equilibrate for a period of at least 48 hours.

The range of water contents for each soil were selected based on estimates of the critical water content to ensure an equal number of observations on both sides of the point of inflection (Figure 1.2).

Cylindrical moulds 101 mm in diameter and 107 mm height were used. The soil was placed in the mould in five layers of equal thickness and a predetermined number of 25 blows were applied to each layer with a 300 mm stroke using a 4.5 kg drop hammer.

The total mechanically-compacted soil in the mould was weighed. The average gravimetric water content of each sample was determined by taking two subsamples from the mould after weighing. Equation 2.1 was used to calculate the maximum bulk density:

$$BD = \frac{M_w/(1+G)}{\pi R^2 H} \qquad (2.1)$$

Where:

BD – bulk density (Mg m^{-3})

M_w – total mechanically compacted wet sample in the mould (kg)

G – gravimetric water content (unitless)

R – radius of the mould (m)

H – height of the mould (m)

π - Phi = 3.14

Curves for the gravimetric water content to bulk density relationships were plotted to obtain the critical water content and maximum bulk density.

2.3.2 Minimum bulk density

2.3.2.1 Development of a procedure for the minimum bulk density determination

The concept of minimum bulk density in based on a proposal by Bennie &Van Antwerpen (1988). According to these authors, the soil should be poured freely into a

static mould through a funnel. The mould should then be scraped to remove the excess soil. The mass of the soil in the mould and its volume is used to calculate the minimum bulk density. The specifications of the equipment and the conditions for this determination need to be standardised.

Experiments were conducted to get a method that will give reliable results. For these experiments the hypothesis was that four main factors can influence the procedure, namely, the diameter of the mould, the falling height of the soil, the size of the soil particles and the "falling uniformity" of the particles. Therefore, experiments comprising combination of all these factors were performed.

To investigate the effect of the size of the moulds two moulds both with a height of 100 mm but with different diameters of 106 mm (small) and 158 mm (large) were used. To obtain different falling heights, sleeves with the same diameter as the moulds but with different lengths were placed on top of the moulds. The pouring heights were 0 mm, where no sleeve was placed on the top of the mould and the soil was poured directly over the edge into the mould, 150 mm, 300 mm and 450 mm. To give a more even spread of soil particles during the pouring action a wire mesh with 6.5 mm openings was placed 20 mm from the top of each sleeve (Figure 2.1).

Six soils were selected which had silt plus clay contents of 8 to 41%. Samples were oven dried, passed through a 6 mm sieve and subjected to the seven treatments described in Table 2.2. Each treatment was replicated 20 times for both, the small and the large moulds.

Using a glass beaker of 800 ml the soil was poured to fill the moulds from the set height according to the treatment. When the mould was full, the sleeve was removed and a knife was used to scrape the excess soil from the top of the cylinder. The soil in the mould was weighed for later calculation of the minimum bulk density. For the 0 mm falling height it was impractical to include a mesh.

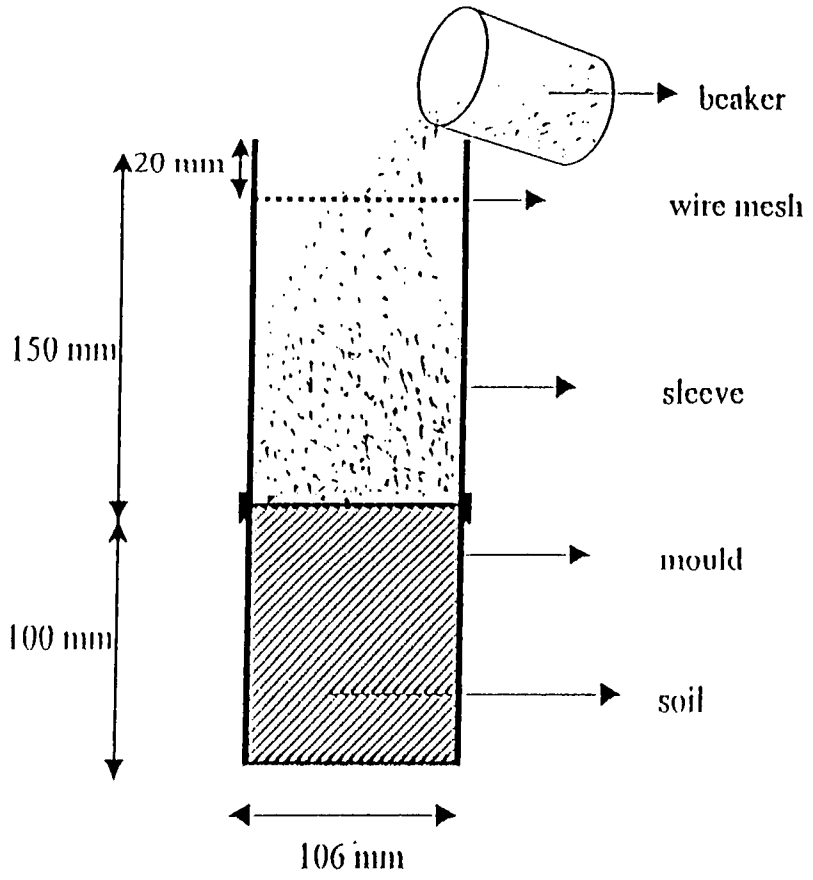


Figure 2.1: Illustration of the apparatus used for determining the minimum bulk density of the soils.

Table 2.2: Treatments for the representative soils

Treatment	Falling height (mm)	Condition
1	(0= On top of the cylinder)	Without mesh
2	150	Without mesh
3	150	With mesh
4	300	Without mesh
5	300	With mesh
6	450	Without mesh
7	450	With mesh

Falling height versus bulk density graphs were plotted with and without the mesh. From the graphs in the Figures 2.2a, b, c, d, e and f, it can be concluded that the general trend is an increase in bulk density from 0 to 150 mm after which the bulk density remains constant or the decrease is insignificant. The most probable reason for this observation is that a falling distance of 150mm is sufficient to obtain a maximum arrangement of the particles and 150 mm could be considered as the optimum falling height.

The mean minimum bulk density of the 20 replications for each treatment and soil was calculated as well as the coefficient of variance (Table 2.3). The treatment with the smallest coefficient of variance was regarded as the one with the best reproducibility. The small mould combined with the mesh had the least variation . Based on the referred

(B1A)

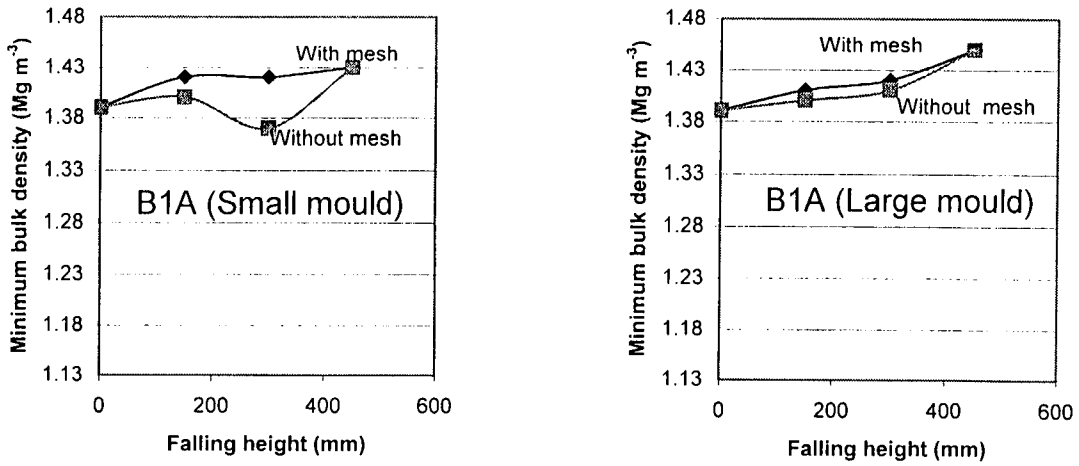
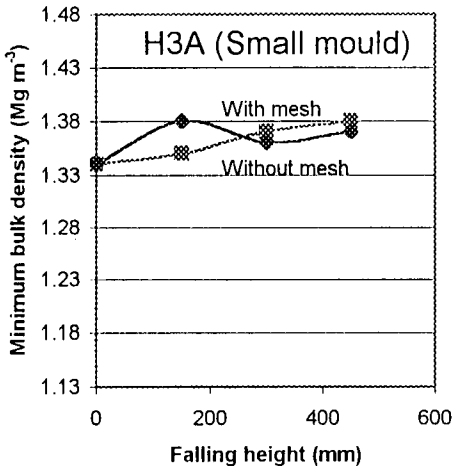
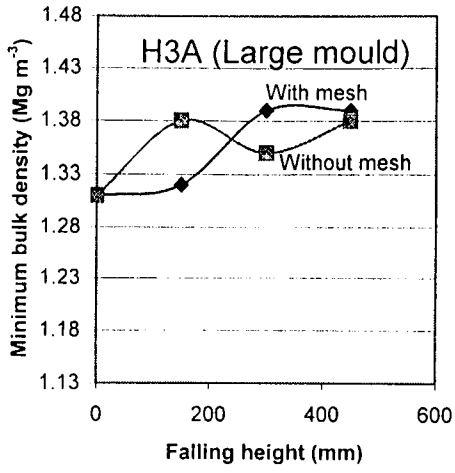


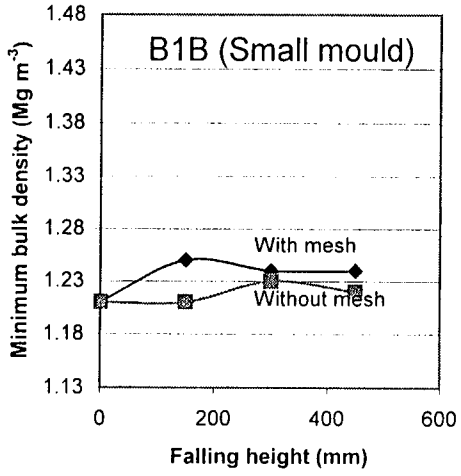
Figure 2.2: Minimum bulk density from different treatments for selected soils.

(H3A)





(B1B)



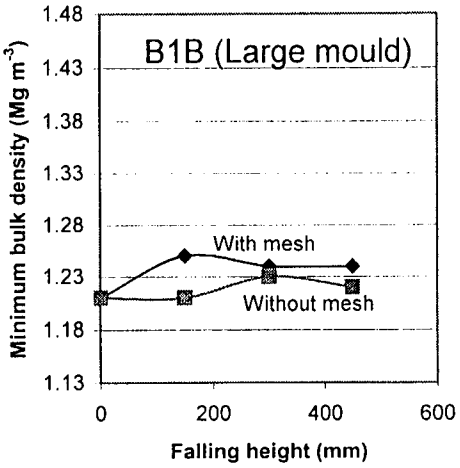
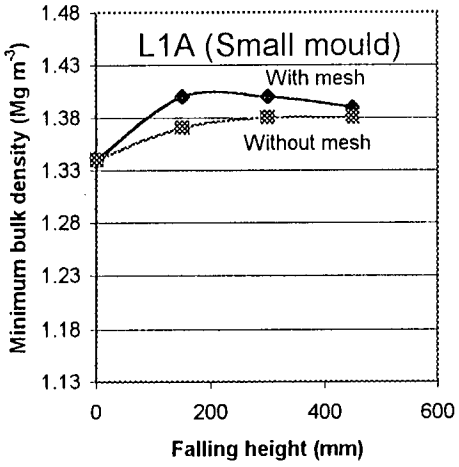
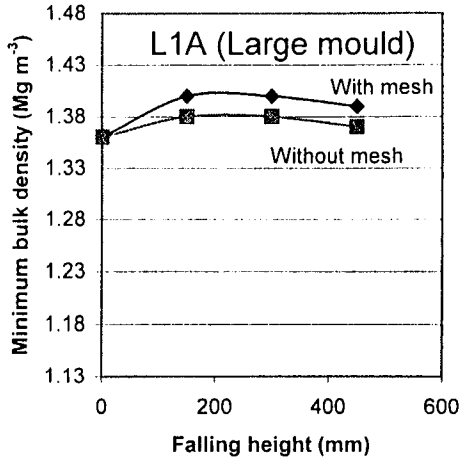


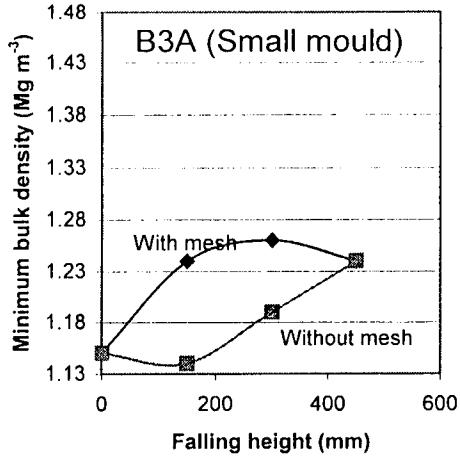
Figure 2.2 Continued.

(L1A)





(B3A)



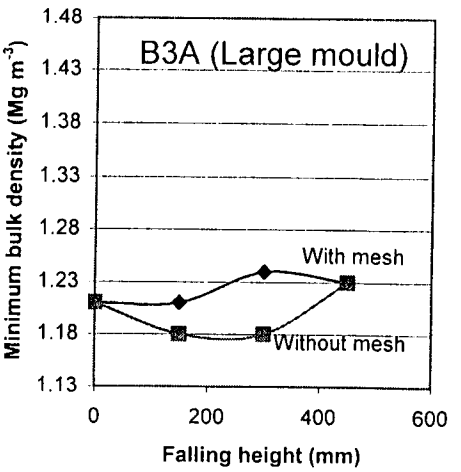


Figure 2.2: Continued.

(T1A)

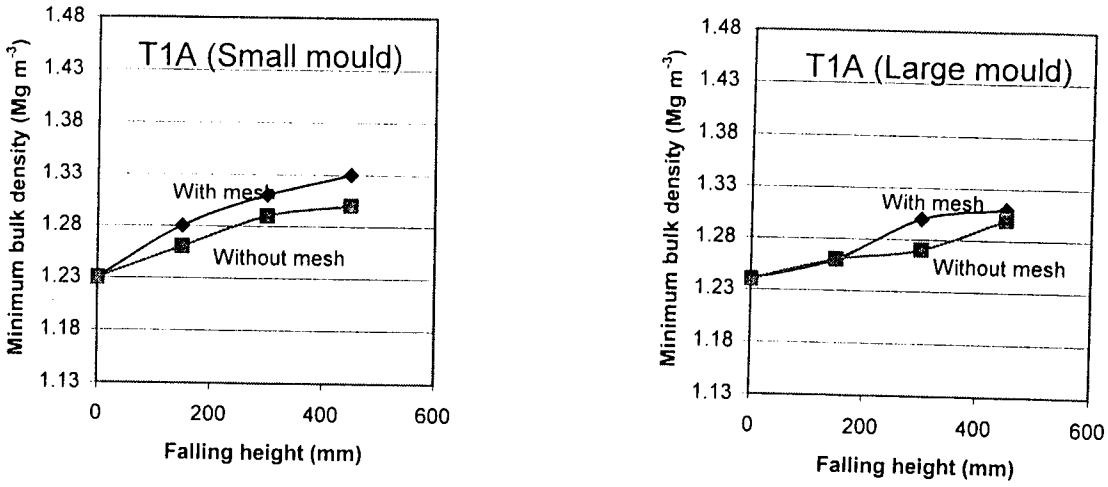


Figure 2.2: Continued

Figures and the results in the Table 2.3, it was decided to standardise on a sleeve of 106 mm diameter and 150 mm height with a mesh. The sleeve was placed on the top of the 106 mm diameter mould with a height of 100 mm.

After standardising the apparatus a second experiment was performed using 6 and 2 mm sieved samples. The mean minimum bulk density values and coefficients of variation are presented in Table 2.4. The soil passed through a 2mm sieve produced more consistent results than the 6mm sieved soils. The 6mm sieved soils had some aggregates. These aggregates were probably the major source of variation as the arrangement was not always uniform. Thus, the final conclusion reached was that the mould with 106 mm internal diameter combined with a sleeve allowing for a falling height of 150 mm using a mesh and 2 mm oven dry sieved soil was the procedure with the highest degree of repeatability, giving the most consistent results.

Table 2.3: Minimum bulk densities of 6 mm sieved samples of selected soils from different treatments.

		Small mould				Large mould			
		With mesh		No mesh		With mesh		No mesh	
SOIL	Height	BD	CV	BD	CV	BD	CV	BD	CV
	(mm)	(Mg m^{-3})	(%)	(Mg m^{-3})	(%)	(Mg m^{-3})	(%)	(Mg m^{-3})	(%)
B1A	0	-	-	1.39	0.50	-	-	1.39	2.22
	150	1.42	0.27	1.4	0.35	1.41	0.46	1.40	1.66
	300	1.42	0.31	1.37	0.38	1.42	1.72	1.41	9.46
	450	1.43	0.33	1.43	0.35	1.45	0.69	1.45	0.69
H3A	0	-	-	1.34	0.80	-	-	1.31	0.97
	150	1.38	0.52	1.35	0.56	1.32	1.09	1.38	0.40
	300	1.36	0.39	1.37	0.51	1.39	0.75	1.35	0.81
	450	1.37	0.60	1.38	0.40	1.39	0.53	1.38	1.59
B1B	0	-	-	1.21	1.09	-	-	1.21	1.22
	150	1.25	0.53	1.21	1.21	1.25	0.74	1.21	3.79
	300	1.24	0.59	1.23	0.87	1.24	0.61	1.23	0.90
	450	1.24	0.60	1.22	0.99	1.24	1.04	1.22	1.14
L1A	0	-	-	1.34	1.03	-	-	1.36	1.18
	150	1.40	0.43	1.37	0.61	1.40	0.65	1.38	0.85
	300	1.40	0.38	1.38	0.73	1.40	0.77	1.38	0.74
	450	1.39	0.89	1.38	0.46	1.39	0.90	1.37	0.63
B3A	0	-	-	1.15	2.14	-	-	1.21	2.52
	150	1.24	0.48	1.14	1.22	1.21	1.69	1.18	4.69
	300	1.26	1.68	1.19	2.58	1.24	1.24	1.18	2.64
	450	1.24	0.67	1.24	1.55	1.23	2.57	1.23	2.65
T1A	0	-	-	1.23	1.71	-	-	1.24	1.79
	150	1.28	1.29	1.26	1.76	1.26	1.52	1.26	1.76
	300	1.31	0.76	1.29	1.33	1.30	1.09	1.27	1.43
	450	1.33	0.72	1.3	1.43	1.31	0.75	1.30	1.41

Table 2.4: Minimum bulk densities of 6mm and 2mm sieved samples of selected soils.

	6mm sieved		2mm sieved soil	
SOIL	$BD^{(*)}$	$CV^{(**)}$	$BD^{(*)}$	$CV^{(**)}$
B1A	1.42	0.29	1.43	0.19
H3A	1.37	0.48	1.39	0.15
B1B	1.25	0.59	1.24	0.49
L1A	1.40	0.38	1.39	0.21
B3A	1.26	0.53	1.29	0.16
T1A	1.28	1.27	1.32	0.50

$^{(*)}$ BD – Minimum bulk density (Mg m^{-3}); $^{(**)}$ CV. – Coefficient of variance (%)

2.3.2.2 Minimum bulk density determination

Following the decisions taken to standardise the procedure, as described in Section 2.3.2.1, 2 mm sieved samples from the 22 soils were used to determine the minimum bulk density in triplicate using a mould with 106 mm internal diameter and 100 mm height. A sleeve with the same diameter as the mould and 150 mm height was positioned on the top of the mould and the soil was poured through a mesh with 6.5 mm openings placed 20 mm from the top of the sleeve, to fill the mould. Then, the sleeve was removed and the excess soil above the mould was scraped using a sharp and levelled knife. The remaining soil inside the mould was weighted. This mass was divided by the volume of the mould to obtain the minimum bulk density expressed in Mg m^{-3}.

2.4 Organic matter content

The organic matter content was determined using two methods: the organic carbon content with the wet oxidation method (Walkley-Black method) and the Loss- On-Ignition (LOI). All the determinations were carried out in triplicate.

The wet oxidation following the Walkley-black method was performed as described by The Non-Affiliated Soil Analysis Work Committee (1990) after grinding the soil to pass through a 0.35mm sieve and the organic carbon was calculated as a percentage on a mass basis.

The LOI was calculated from the loss in mass after ignition at 450°C of 15g of soil for a period of at least 1 hour as recommended by Donkin (1991). Similarly to organic carbon, the results were expressed as percentage of oven dry mass of soil.

2.5 Compression index

Fourteen sub-samples of each soil were wetted in plastic bags to a gravimetric water content corresponding to the critical water content obtained during the maximum bulk

density determination and were sealed to prevent evaporation. To allow for an equal distribution of water, the samples were placed in a relatively constant temperature environment for a period of at least 48 hours, and were shaken twice a day.

A stainless steel cylinder 80 mm in diameter and 80 mm high, with a perforated base, to allow air to escape during compression, was used to determine the stress-bulk density relationship for each subsample of soil, using an hydraulic press. The moist soil samples were filled and compressed into the cylinder in five layers. Each soil sub-sample and the respective layers were compressed to a specific pressure using an hydraulic pressure gauge connected to a piston. A hand pump was used to generate the required pressure on the soil. Each moist sample fraction was poured loosely into the cylindrical container and compressed to a predetermined pressure. The pressure was kept constant for about 5 seconds and then released (Smith, 1995). The soil samples, were subjected to applied pressures of 129, 233, 466, 672, 905, 1138, 1578 kPa. In sandy soils, additional pressures of 1810 and 2070 kPa were added to increase the range. The compression levels were selected to provide a reasonable number of observations. All the measurements were done in duplicate. The apparatus used for this determination is shown in the Figure. 2.3.

The height of the soil in the cylinder, after a compression test was completed, was determined by measuring the distance between the upper edge of the cylinder and the soil core at four places with a micrometer. These values were later used to calculate volume of the soil core. The bulk density could then be calculated from the oven dry weight and the volume of the soil core.

For each soil, a compression line relating bulk density to the logarithm of the applied pressure was obtained. The compression index was computed as the slope of linear portion of the curve, called the virgin compression line (VCL, Figure 1.1). The slopes of these lines were calculated using regression techniques.

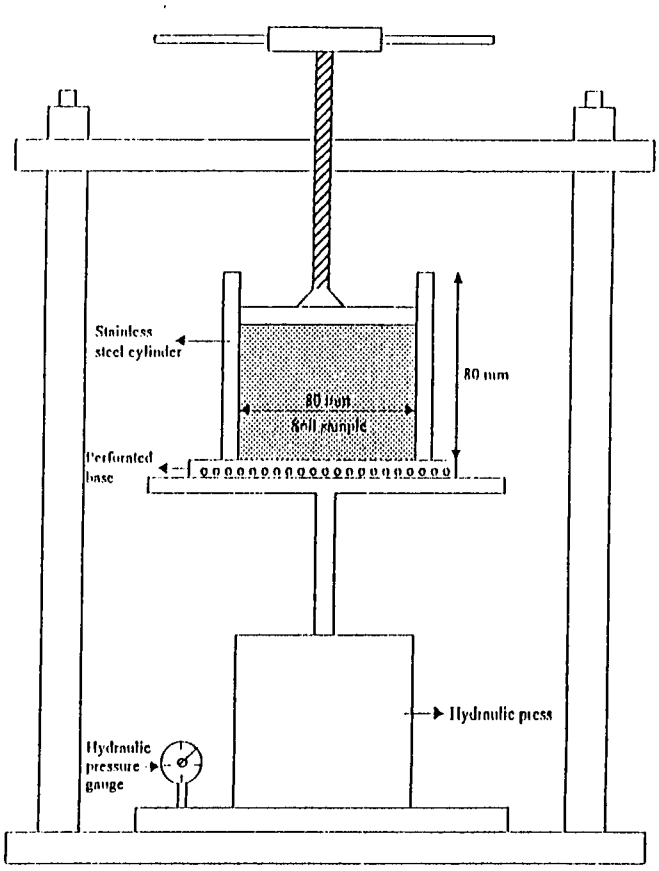


Figure 2.3: Apparatus used for uniaxial compression.

2.6 Penetrometer resistance

The soil core samples from the compression index tests were also used for the determination of penetrometer resistance in unconfined conditions before the samples were placed to dry in an oven. A 3 mm base diameter probe with a 30° semi-angle cone-shaped point was pushed mechanically vertical into the soil at a constant rate of 10 mm h^{-1} (Bennie & Botha, 1988). The diameter of the probe is reduced to 2mm at a distance of 8 mm behind the point to reduce the area of soil-steel friction.

All the readings were taken at a depth ranging from 40 to 50 mm. Five readings were made per cylinder. Care was taken to avoid the cylinder wall interfering with the readings. One reading was taken in the centre of the cylinder core while the other four were equally distributed on the points 15mm from the wall of the cylinder. The five

readings in each cylinder were averaged to obtain the mean value. These values were expressed in MPa.

The sample was then weighed and dried to determine actual gravimetric water content and the dry bulk density. These data were used to plot a bulk density-penetrometer resistance graph at a constant water contents for each soil.

CHAPTER 3
SOIL PROPERTIES AFFECTING THE MAXIMUM AND MINIMUM BULK DENSITY OF SOILS

3.1 Introduction

When a soil is subjected to a mechanical force, the physical properties will change due to compaction. This process involves bringing solid soil particles closer together (Bodman & Constantin, 1965). When such rearrangement occurs, the bulk volume of the soil diminishes and the bulk density increases. Thus, if an increasing stress is applied to loosely packed soil, the bulk density will increase until it reaches the maximum bulk density (Larson *et al.*,1980). At the maximum bulk density, void spaces between the larger fractions are filled with small particles.

Very little research has been done regarding the concept of minimum bulk density. Gupta & Larson (1979) have calculated the minimum bulk density based on a computer packing model. The computer model calculates the total bulk volume that results when all soil particles are stacked randomly on top of each other without any mixing, representing the "loose state" of any mixture of particles. Bennie & Antwerpen (1988) suggested an approach consisting of pouring soil into a cylinder. None of these approaches have addressed the role of the intrinsic soil properties on the minimum bulk density.

There is general agreement that the maximum density to which a soil can be packed by a standard amount of energy, termed "compactibility", is influenced by external and internal factors. The external factors comprise of various natural and man made stresses arising mainly from soil management actions (Raghavan, McKyes, Gendron, Borglum & Le 1978 and Da Silva *et al.*, 1997). The internal factors are the physico-mechanical properties which depend on the soil type and water content (Ekwe & Stone, 1995 and Etana *et al.*,1997). This is the reason why soil type must be included in relationships to

predict changes in bulk density when a mass of soil is subjected to a given condition of stress (Harris, 1971).

The soil types are mainly characterised by mineral and organic fractions. Larson *et al.* (1980) stated that the important factors include particle size distribution, nature of the clay fraction and organic matter contents while Bradford & Gupta (1986) also included soil fabric and structure, particle surface forces and pore water chemistry. The median particle size, particle shape and surface roughness have been suggested by Panayiotopoulos & Mullins (1985) but later they realised that there was little direct evidence of the effect of particle shape on packing. Bodman & Constantin (1965) have stressed that a given quantity of solid particles with a suitable geometric shape might be rearranged by compaction in such a manner that all voids are destroyed, but it is improbable that such a condition would ever occur in nature.

Organic matter plays an important role in improving the mechanical and physical properties of cultivated soils, although there is still limited appreciation for the role of organic matter in the compactibility of agricultural soils (Soane, 1990). According to Angers (1990), Gupta & Larson (1982) found a high correlation between bulk density and clay content but not with organic matter content. Angers (1990) cited De Kimpe *et al.*, (1982) who found a strong negative relationship between the maximum dry bulk density and organic carbon content when performing Proctor compaction tests on soils from Quebec (Canada). Ekwe & Stone (1995) found that the increase in soil strength parameters with increasing compactive effort were affected by soil texture and the type of organic matter.

Water content is the most important factor influencing soil compactibility, hence the maximum bulk density attained in the compaction procedure is strongly dependent upon the water content (Van der Watt, 1969 and Mirreh & Ketcheson, 1972). According to Harris (1971) and Scholefield, Patto & Hall (1985) this is because soil properties like volume change, strength, plasticity and compactibility are particularly determined by water content. Hamdani (1983) ascribed the effect of water to its lubrication effect.

Higher water contents lubricate better, but at very high contents it may limit compaction because water instead of air must be squeezed out during short loadings (Koolen, 1987)

The water content corresponding with the peak of the curve (Figure 1.2) is defined as the "optimum water content" of the soil (Bradford & Gupta, 1986). This term is widely used but for the purpose of this research it was replaced by "critical water content" as proposed by Smith (1995) who argued that the former term has engineering connotations. Etana *et al.* (1997) stated that "critical water content" reflects the negative effect of soil compaction on arable land.

Gupta & Larson, (1979) were of the opinion that it would be unrealistic to expect accurate predictions of bulk densities in soil profiles because of the many factors influencing the packing arrangements. According to Ekwe & Stone (1995) the interaction between water content and structure is one of the limitations for using simple laboratory tests as an indicator of field behaviour. However, Da Silva *et al.* (1997) stated that it is possible to quantify the effects of intrinsic soil properties and management on bulk density separately for soils derived from similar parent materials and under similar conditions, either by using multiple regression analysis or by normalizing bulk density with respect to a reference bulk density.

Lerink (1990) stated that the comparative prediction method based on a limited domain, has proved to be a useful tool to predict the immediate effect of field traffic during distinct field operations on the soil conditions. Lately, Wagner *et al.* (1994) showed that although the dependence of soil strength on water content and bulk density is complex, these factors can provide a basis for predicting changes in the state of soil compaction and mechanical properties.

The range of bulk densities that can exist for a soil is dependent on the texture (Henderson, Levett & Lisle, 1988). Van der Watt (1969) concluded that the particle size analysis data were sufficient to assess the soil compactibility which could be of prime

importance in evaluating the suitability of soils for various agricultural and engineering purposes. According to Soane (1990), studies have shown that organic matter content may be used as a means of predicting bulk density. Smith *et al.* (1997b) has made a conclusive statement that soil parameters can be assessed accurately by soil properties which are routinely measured in the laboratory or assessed in the field during the course of soil surveys. However, Felt (1965) had made an important remark that compactibility relationships depend to some extent on the type of equipment used for compaction.

Particle size distribution, organic matter and water content are soil properties measured on a routine basis in investigations. It would be worthwhile if this limited number of soil properties could be used to predict the maximum and minimum bulk densities as means of assessing the effectiveness of soil cultivation.

3.2 Results and Discussion

The localities where the soils were collected, sample coding and classification according to soil texture, Taxonomic System for South Africa, as well as the silt and clay contents of the soils are shown in the Table 3.1. The organic matter content, critical water content, maximum and minimum bulk densities are summarised in Table 3.2. The graphs of bulk density as a function of water content can be found in Appendix 3.1.

In order to make the discussion and interpretations easier, the relationship among the different soil properties will be discussed, followed by the properties that can be related to the maximum and minimum bulk densities respectively.

Table 3.1: Texture of the soils studied

Code	Soil Classification		Silt (%)	Clay (%)	Silt + Clay (%)	Soil Texture (*)
	Soil Form	Family				
B1A	Bainsvlei	Amalia	5	3	8	Sa
B2A	Hutton	Stella	7	2	9	Sa
B1B	Bainsvlei	Amalia	17	3	20	LmSa
B3A	Valsrivier	Luckhoff	7	21	28	SaClLm
D2B	Hutton	Stella	4	18	22	SaLm
D3A	Valsrivier	Luckhoff	15	31	46	SaClLm
D1B	Valsrivier	Luckhoff	21	33	54	SaClLm
D1A	Valsrivier	Luckhoff	24	40	64	Cl
G1A	Bonheim	Mkuze	23	45	68	Cl
H5A	Clovelly	Setlagole	4	1	5	Sa
H2A	Clovelly	Setlagole	6	1	7	Sa
H4A	Avalon	Kameelbos	7	2	9	Sa
H3A	Clovelly	Mooilaagte	7	4	11	Sa
H1A	Hutton	Stella	9	3	12	Sa
H1B	Hutton	Stella	16	5	21	LmSa
L3A	Avalon	Mafikeng	5	10	15	LmSa
L2A	Clovelly	Mooilaagte	9	7	16	LmSa
L1A	Clovelly	Mooilaagte	14	9	23	SaLm
L3B	Avalon	Mafikeng	10	21	31	SaClLm
L1B	Avalon	Mooilaagte	19	13	32	SaLm
T2A	Westleigh	Mareetsane	13	11	24	SaLm
T1A	Swartland	Adelaide	25	16	41	SaLm

(*) Sa-Sandy, SaClLm-Sandy clay loam, LmSa-Loamy sand, Cl-Clay

Table 3.2: Important properties of the soils

Code	Soil form	Soil Texture	Silt + Clay	CWC* (%)	Organic matter		Max BD (Mg m^{-3})	Min BD (Mg m^{-3})
					OC (%)	LOI (%)		
B1A	Bainsvlei	Sa	8	8.61	0.35	1.33	1.84	1.43
B2A	Hutton	Sa	9	8.52	0.21	1.5	1.87	1.38
B1B	Bainsvlei	LmSa	20	10.69	0.43	3.8	1.99	1.24
B3A	Valsrivier	SaClLm	28	10.95	0.50	4.5	1.97	1.35
D2B	Hutton	SaClLm	22	10.4	0.25	3.3	2.03	1.22
D3A	Valsrivier	SaClLm	46	15.2	0.62	7.4	1.83	1.16
D1B	Valsrivier	SaClLm	54	16.1	0.68	7.3	1.76	1.17
D1A	Valsrivier	Cl	64	18.5	0.77	9.1	1.73	1.21
G1A	Bonheim	Cl	68	20.83	1.16	11.1	1.6	1.15
H5A	Clovelly	Sa	5	9.94	0.21	1.0	1.76	1.48
H2A	Clovelly	Sa	7	8.0	0.16	1.4	1.85	1.40
H4A	Avalon	Sa	9	9.1	0.40	1.2	1.81	1.40
H3A	Clovelly	Sa	11	8.6	0.21	1.7	1.91	1.39
H1A	Hutton	Sa	12	8.0	0.21	2.1	1.95	1.35
H1B	Hutton	LmSa	21	10.57	0.21	3.4	2.0	1.21
L3A	Avalon	LmSa	15	9.74	0.53	2.6	1.93	1.34
L2A	Clovelly	LmSa	16	8.0	0.31	1.9	1.94	1.39
L1A	Clovelly	SaLm	23	8.29	0.41	2.2	1.95	1.39
L3B	Avalon	SaClLm	31	10.86	0.36	3.9	1.99	1.23
L1B	Avalon	SaLm	32	10.38	0.50	3.1	1.99	1.27
T2A	Westleigh	SaLm	24	10.43	0.46	2.8	1.97	1.29
T1A	Swartland	SaLm	41	11.3	0.91	4.4	1.91	1.32

* = Critical water content

3.2.1 Relationships between the different soil properties

Figures 3.1 and 3.2 show the indicators of organic matter content namely the organic carbon (%) and loss on ignition (%) as functions of the silt plus clay contents using different techniques. Both relationships are linear and can be represented by the Equations 3.1 and 3.2. The most probable explanation for the measured increase in organic matter content with increasing silt plus clay is that as the silt plus clay fraction increases in soils, there is an increase in specific surface which creates a large area to which organic particles can be adsorbed to form organo-clay complexes.

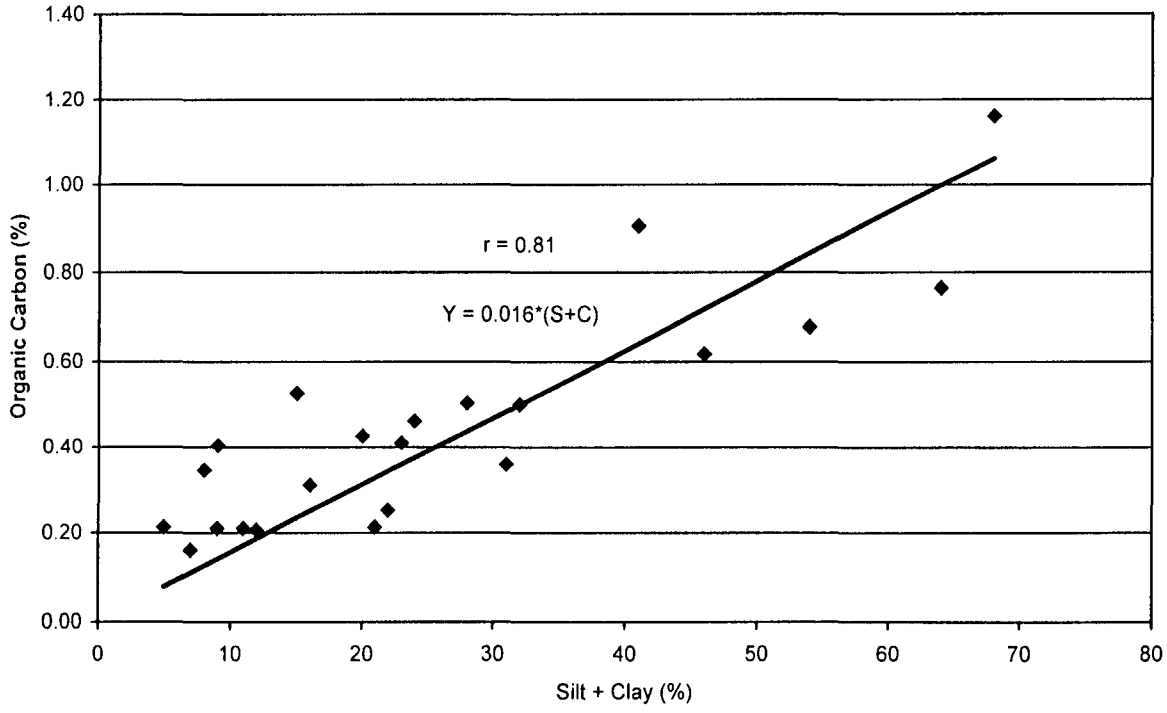


Figure 3.1: Organic carbon as a function of silt plus clay content.

$$OC(\%) = 0.01562 * (S+C\%) \qquad r = 0.81 \qquad (3.1)$$

$$LOI(\%) = 0.14281 * (S+C\%) \qquad r = 0.96 \qquad (3.2)$$

The relationship between silt plus clay and organic matter content is best explained when the organic matter is determined in terms of loss on ignition (LOI).

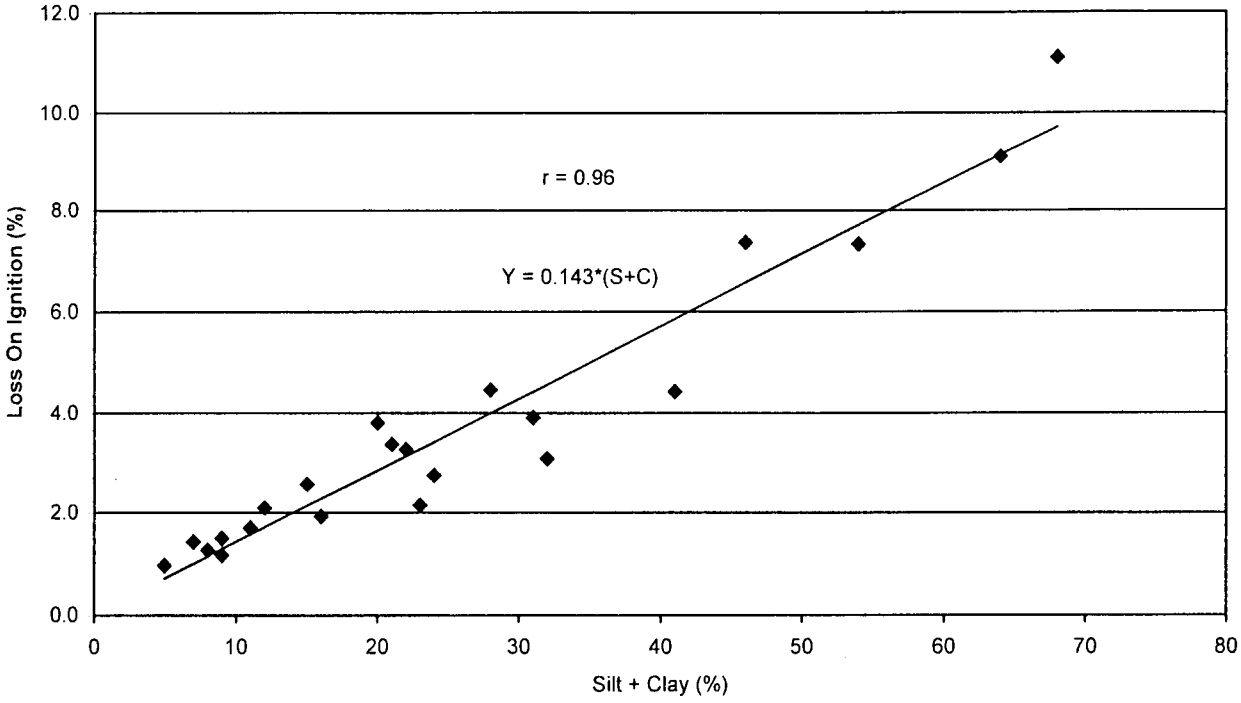


Figure 3.2: Loss on ignition as a function of silt plus clay content.

As shown in Figure 3.3 the organic carbon (OC) is also related to the LOI (Equation 3.3).

$$OC\ (\%) = 0.107 * (LOI\%) \qquad r = 0.74 \qquad (3.3)$$

The low R-value (0.70) shows that this prediction is relatively poor compared to the previous ones. The equation is different from the one recommended by Donkin (1991) using LOI as an estimator of organic carbon with the following formula: OC=0.284*LOI. The range of soils used for this study is more sandy compared to soils used by Smith (1995) whereas Donkin (1991) used even more clayey soils. Considering the results found from this research and the explanation by Smith (1995), it seems that the conversion factor from LOI to OC depends on the type and the range of soils involved.

The good relationship between LOI and silt plus clay shown in the Figure 3.2, combined with the fact that loss on ignition is a simple technique for estimating organic matter content it was decided to use LOI as an indicator of organic matter content.

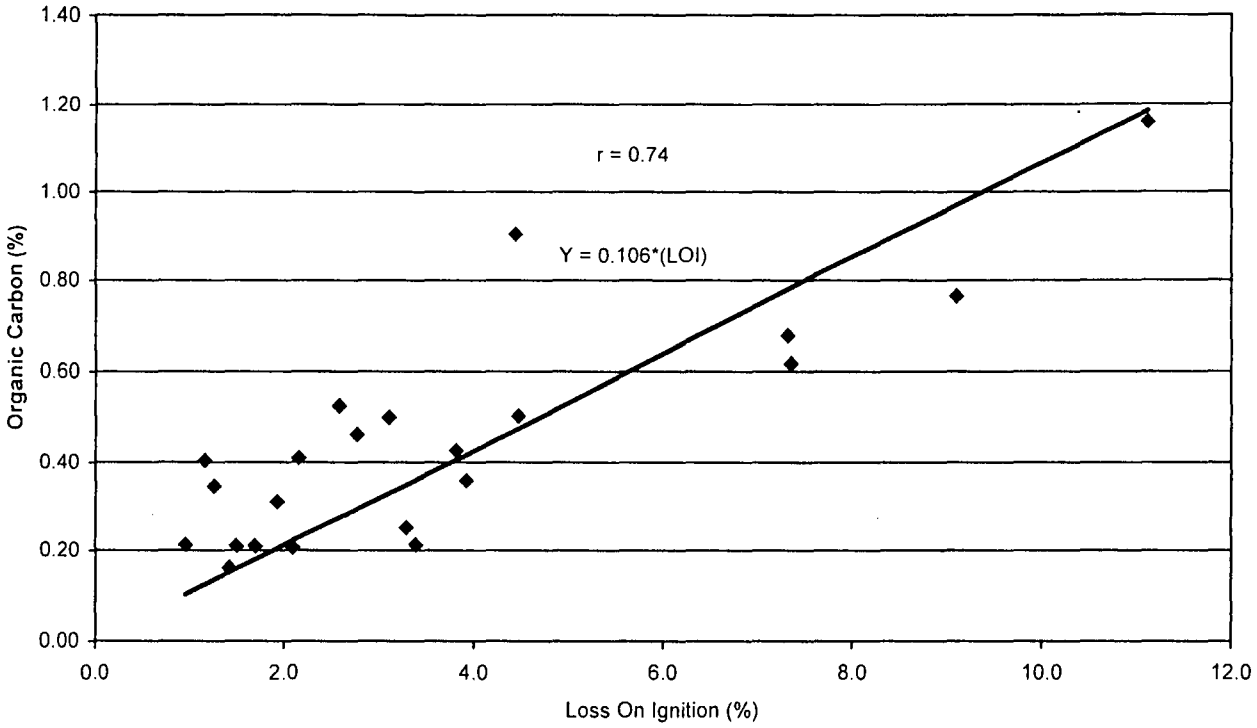


Figure 3.3: Organic carbon as function of loss on ignition.

3.2.2 Maximum bulk density

The maximum bulk density was related to the silt + clay contents and loss on ignition in the Figures 3.4 and 3.5, respectively. Figure 3.4 shows a curvilinear relationship between the silt plus clay (%) and the maximum bulk density (BD_{max}). Harris (1971) has given a probable explanation for this behaviour. According to him, it depends on the degree of grading of the soil particles. Well-graded soils contain equal amounts of coarse and fine-grained particles and will have more contacts between particles and filling of inter-particle voids resulting in a high maximum bulk density. Poorly graded soils contain particles of more or less the same size that cannot fit into the voids between particles resulting in a lower maximum bulk density. In this case, well-graded soils occur at silt plus clay contents around 25% and exhibit the highest maximum bulk density of about 2.0 Mg m^{-3}. The lower values for the more sandy and clayey soils result from the poorer grading due to higher sand or clay fraction. This critical value of 25% silt plus clay is also in agreement with the range for the South African forestry soils studied by Smith (1995). The best mathematical equation fitting the data was obtained using the following

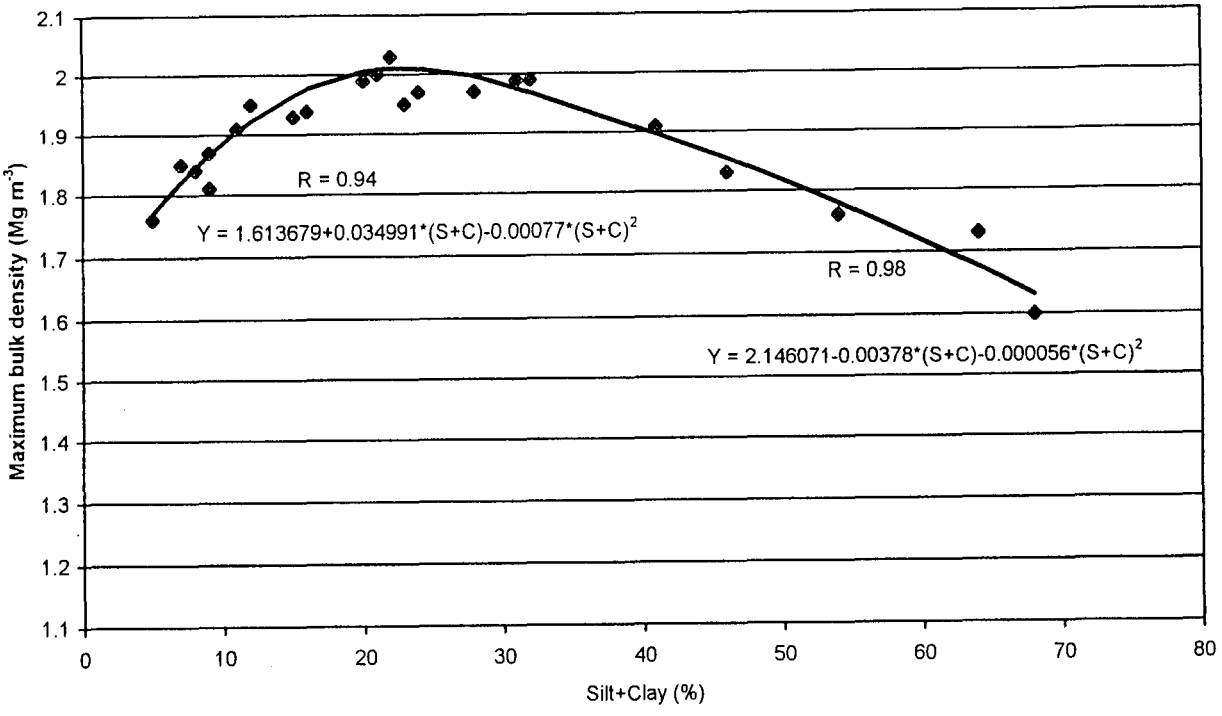


Figure 3.4: Relationship between maximum bulk density and silt plus clay content.

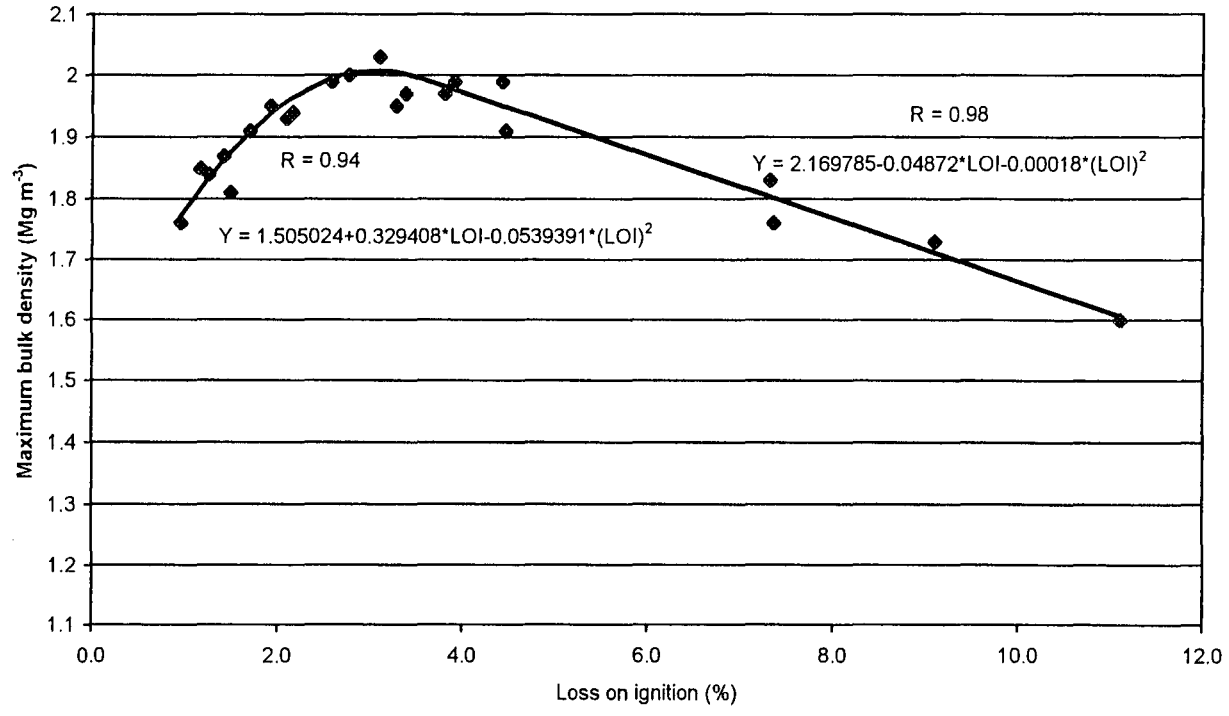


Figure 3.5: Relationship between maximum bulk density and loss on ignition.

procedure: the data was divided into two sets, those with silt plus clay contents lower than 25% and those with higher silt plus clay contents. Quadratic equations were fitted through the data of each set. The bulk density of 2.01 Mg m^{-3} corresponding with 25% silt plus clay was calculated with the <25% equation. The higher than 25% silt plus clay equation was calculated forcing it through 2.01 Mg m^{-3} at 25% silt plus clay. The total relationship is therefore explained by the two quadratic equations (Equations, 3.4a and 3.4b).

S+C < 25%:

$$BD_{max}(Mg\ m^{-3}) = 1.614 + 0.034991*(S+C\%) - 0.00077*(S+C\%)^2 \qquad R = 0.94 \quad (3.4a)$$

S+C > 25%:

$$BD_{max}\ (Mg\ m^{-3}) = 2.146 - 0.00378*(S+C\%) - 0.000056*(S+C\%)^2 \qquad R = 0.98 \quad (3.4b)$$

Apparently, the decrease in void volume due to the rearrangement of soil particles during the compaction process is not similar for the poorly graded more sandy or clayey soils. For silt plus clay contents less than 25% the increase in maximum bulk density due to increase of finer particles is more pronounced compared with the more gradual decline for the more clayey soils. The dominant sand particles in sandy soils create a rigid matrix with large voids that can be filled with the smaller silt and clay particles resulting in a denser soil. This mode of packing reaches an optimum at 25% silt plus clay. When the silt plus clay increases beyond 25%, there is an abundance of small particles in which the larger particles are embedded. According to Felt (1965) a group of small particles occupy a larger volume than a single large particle of the same mass. The packing density will therefore decrease when the percentage of small particles, replacing larger sand grains, increases.

The lower R-value of the equation for soils with silt plus clay contents lower than 25% can be ascribed to properties other than texture affecting the compactibility of the soils. The sand fraction has supplementary properties like skewness of distribution and

roundness of the sand particles which were not included in the equation. These properties can affect the prediction of the maximum bulk density as they influence the packing behaviour of the soils. This is the most probable explanation for the relatively higher variation in the maximum bulk density of sandy soils compared to soils with silt plus clay contents higher than 25%. According to Panayiotopoulus & Mullins (1985), the degree of skewness and particle roundness decrease for smaller soil particles. This could be the reason for less variation in the data for the more clayey soils.

The organic matter content, as indicated by the loss on ignition (%), is also a good estimator of maximum bulk density. The predictions are given by Equations 3.5a and 3.5b. The relationships are given if Figure 3.5 which shows the relationship for less and more than 3.6% which corresponds to 25% silt plus clay.

LOI<3.6%:

BD_{max} (Mg m^{-3}) = 1.505 + 0.329408*LOI (%)– 0.0539391*(LOI%)^2 R = 0.94 (3.5a)

LOI>3.6%:

BD_{max} (Mg m^{-3})= 2.170 – 0.04872*LOI(%) – 0.00018*(LOI%)^2 R = 0.98 (3.5b)

3.2.3 Minimum bulk density

Figures 3.6 and 3.7 show the relationships between the silt plus clay and minimum bulk density and loss on ignition and minimum bulk density, respectively. It is clear from these figures that the minimum bulk density decreases with increasing silt plus clay or organic matter content. The decrease in the minimum bulk density is semi-logarithmic which can be explained by the increase in the total porosity of the soil as the fine particles fraction increases (Equations 3.6 and 3.7).

BD_{min} (Mg m^{-3}) = 1.642 – 0.11121 * ln(S+C%) r = 0.85 (3.6)

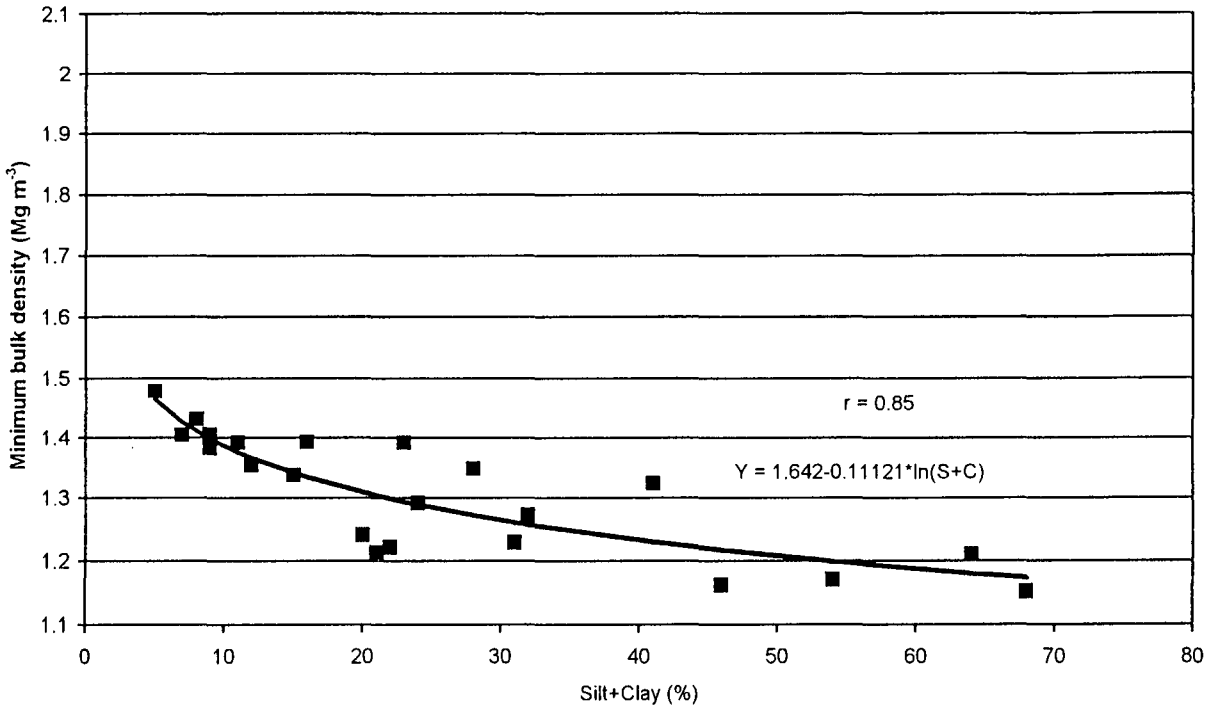


Figure 3.6: Prediction of minimum bulk density from silt plus clay content.

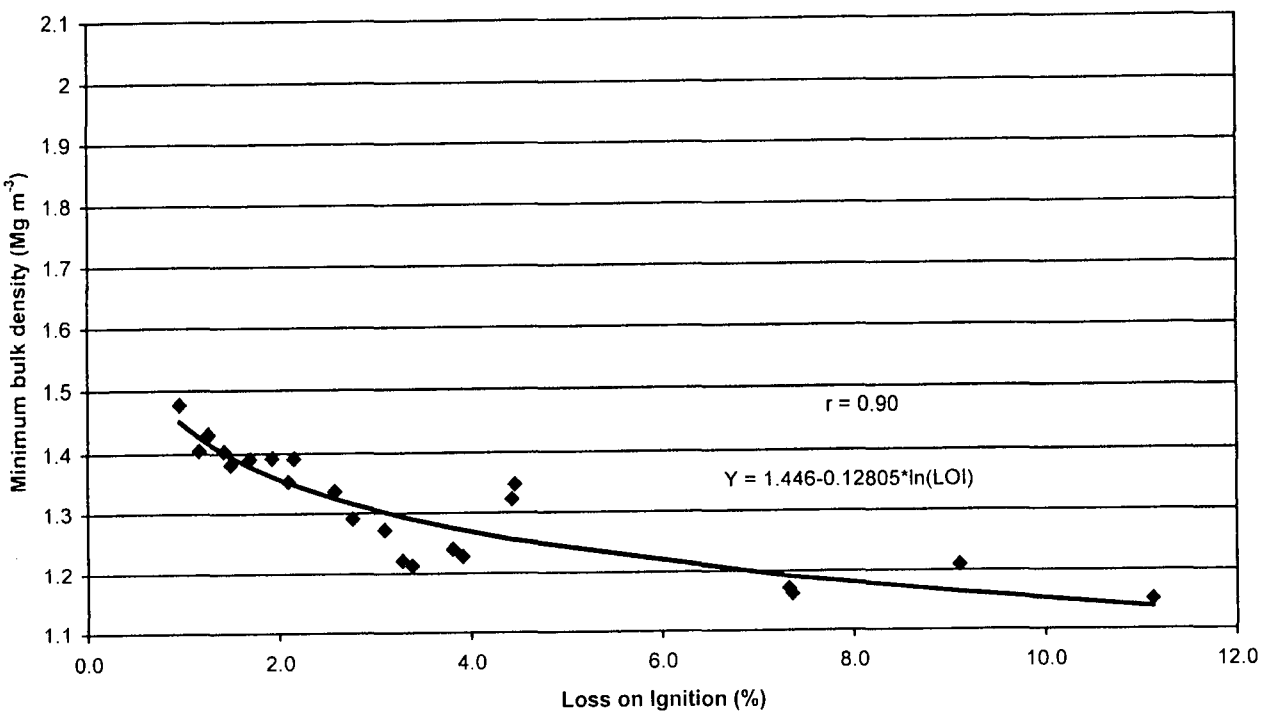


Figure 3.7: Minimum bulk density as affected by loss on ignition.

$$BD_{min}\ (Mg\ m^{-3}) = 1.446 - 0.12805 * \ln(LOI\%) \qquad r = 0.85 \qquad (3.7)$$

The most probable reason for the decline in minimum bulk density is that the method used is a gentle process and arrangement of the particles during the determination played an important role in creating porosity. The decline can also partly be explained by the lower density of the organic matter of which the content increases with increasing silt plus clay contents (Figures 3.1 and 3.2).

The larger R-value of Equation 3.7 indicates that estimating the minimum bulk density from LOI should be more accurate.

3.2.4 Critical water content

The prediction of the critical water content, (CWC, %) where the soil compacts most easily, from silt plus clay content, loss on ignition and maximum bulk density can be done using Equations 3.8, 3.9 and 3.10. The relationships between these properties and the critical water content are shown in Figures 3.8, 3.9 and 3.10, respectively. In Figures 3.8 and 3.9 there is an increase in the critical water content with increase in the independent variable (silt + clay or LOI). Figure 3.10 shows a decrease in critical water content as the maximum bulk density increases.These relationships are in agreement with the explanations given for these relationships. An increase in the fine fraction (silt plus clay) is accompanied by an increase in organic matter content (Figure 3.1). This leads to an increase in the water holding capacity due to an increase in the specific surface area.

$$CWC\ (\%) = 8.747183 - 0.01848*(S+C\%) + 0.002815*(S+C\%)^2 \qquad R = 0.97 \qquad (3.8)$$

$$CWC\ (\%) = 7.55 + 0.647779*LOI\ (\%) + 0.054166*(LOI\%)^2 \qquad R = 0.98 \qquad (3.9)$$

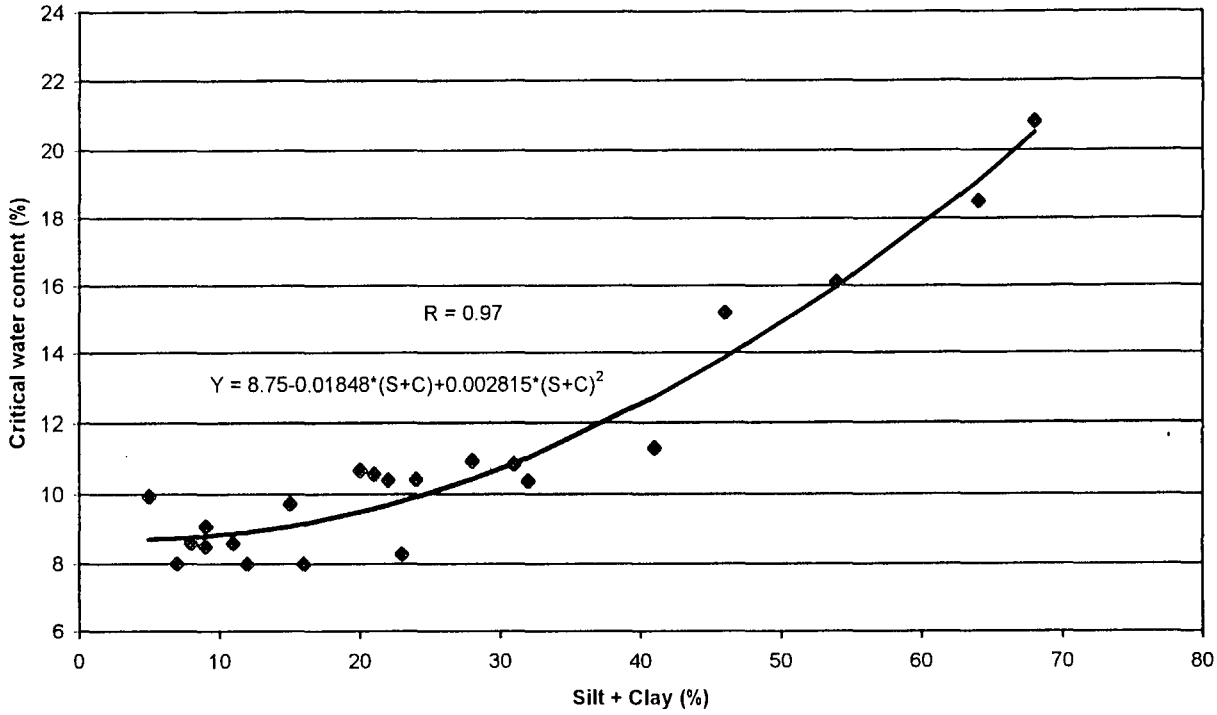


Figure 3.8: Critical water content as function of silt plus clay content.

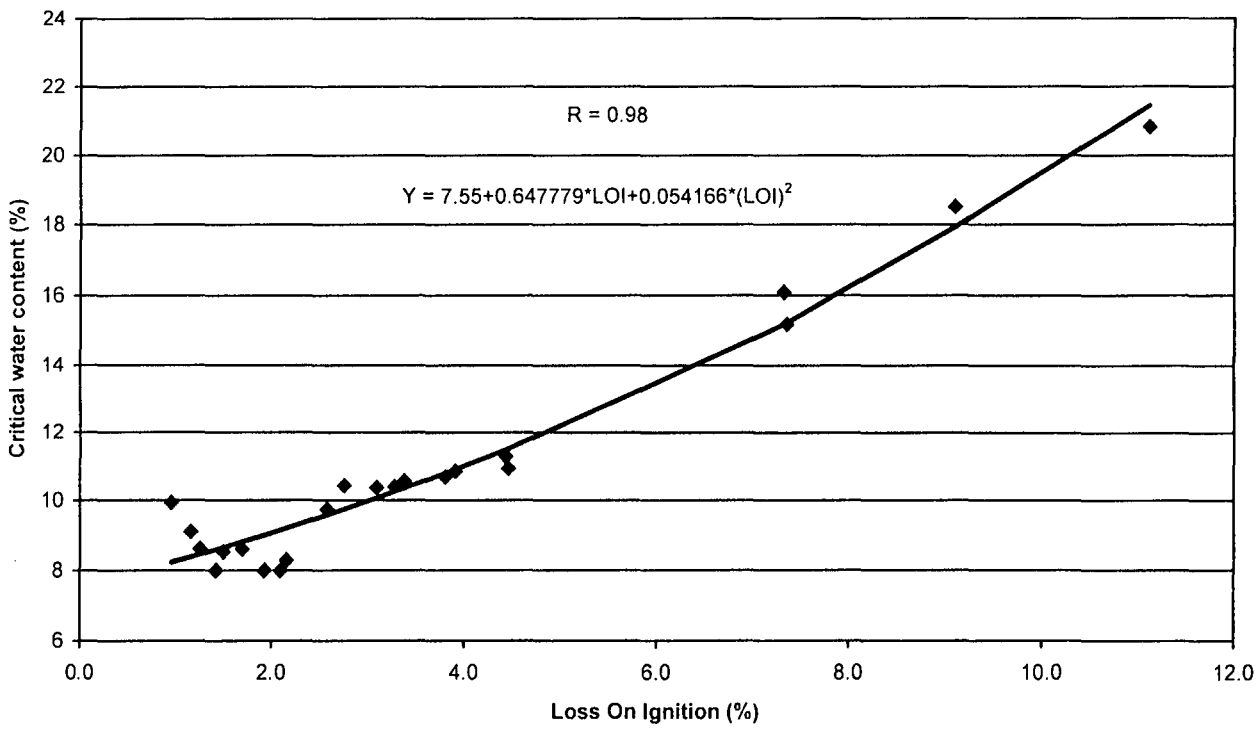


Figure 3.9: Critical water content as function of loss on ignition

There is a negative correlation between the critical water content and maximum bulk density (Figure 3.10 and Equation 3.10). An increasing in maximum bulk density is associated with a higher packing state, thus decreasing the porosity and associated critical water content. As explained in the Section 3.2.2 the degree of packing and consequently the maximum bulk density, depends on the grading of the soils. The less graded soils have lower maximum bulk densities. If the soils are mainly composed of finer particles, more water is required to obtain a sufficient mobility of the particles.

$$CWC\ (\%) = 51.69 - 21.5033*(BD_{max,}\ Mg\ m^{-3}) \qquad r = 0.66 \qquad (3.10)$$

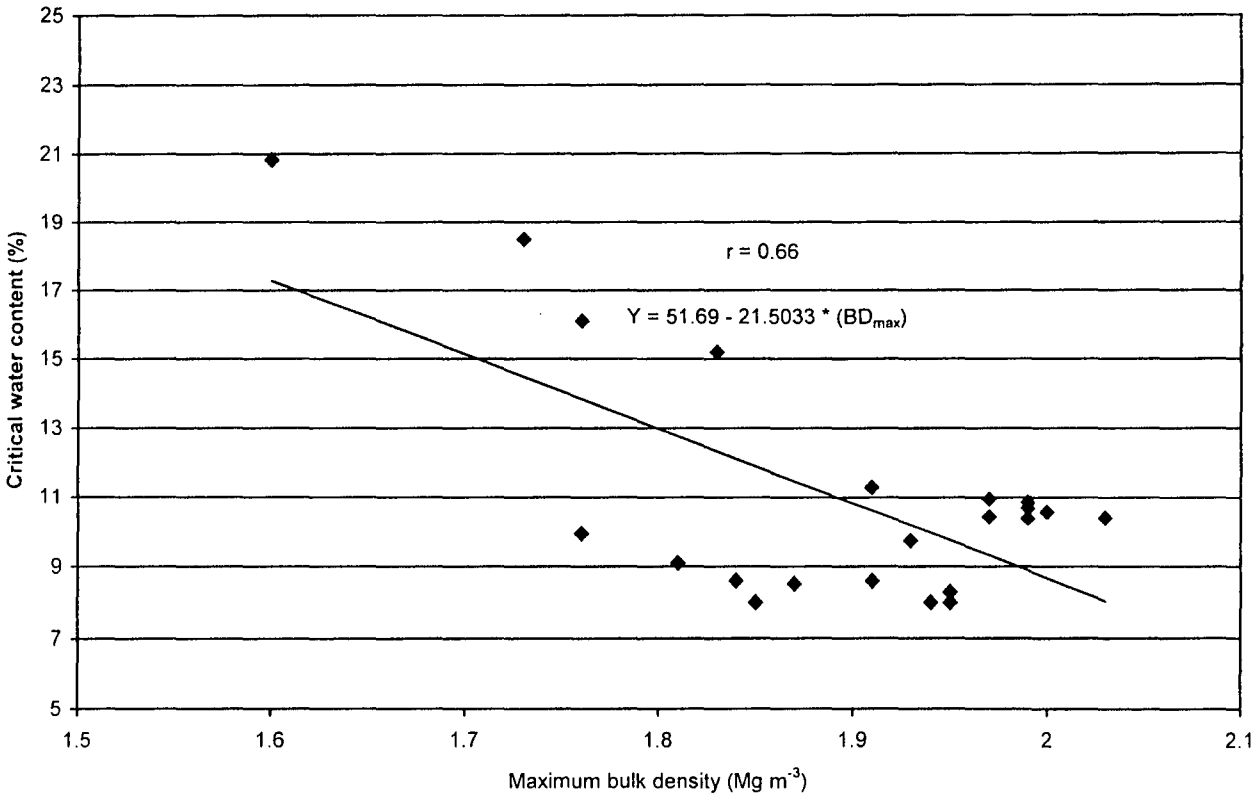


Figure 3.10: Critical water content as a function of maximum bulk density.

3.3 Comparison with the results for forestry soils

In order to make the recommendations of this study more applicable it was decided to compare the results of the current study with the results obtained by Smith (1995) in

other environmental conditions. The maximum bulk density and critical water content data were obtained from Smith (1995). For the determination of the minimum bulk density soil samples were requested from Smith.

The soils studied by Smith (1995) are predominantly fine-textured soils whereas the current study covered mainly coarse textured soils. The uneven textural distribution of the soils does have an influence on the fitting of curves through the data points and the interpretation thereof. Thus, it was decided that the maximum and the minimum bulk density graphs and equations as well as the critical water content functions (Figures 3.4, 3.6 and 3.8) should the compared with the results obtained from the twenty three (23) soil samples supplied by Smith (1995). As texture is widely used to assess the soil physical properties, it was decided that the comparisons were going to be based only on the silt plus clay contents.

3.3.1 Maximum bulk density

The relationships between maximum bulk density and silt plus clay contents for the current study (graph labelled 3), forestry soils (graph labelled 2) and a graph (labelled 1) using the combined data sets are shown in the Figure 3.11. The same curve fitting technique that was explained in Section 3.2.2 was used here. As mentioned earlier, these forestry soils were predominantly clayey and only one soil had a silt plus clay content less than 25%. This value corresponds well with the maximum bulk density of agricultural soils covered by this study. Considering the critical value of 25% silt plus clay that was used to separate the data (Equation 3.4), the forestry soils are only part of the >25% half of the graph. This is the reason why their maximum bulk density can be predicted by a single quadratic equation (graph 2). The maximum bulk density of the soils from this study and the combined data graph can be predicted by two complementary equations (graphs 1 and 3). The two graphs are very similar. The graph for the combined data also shows a critical value of 25% silt plus clay. This observation leads to a suggestion that soils with silt plus clay around 25% are well graded. These soils

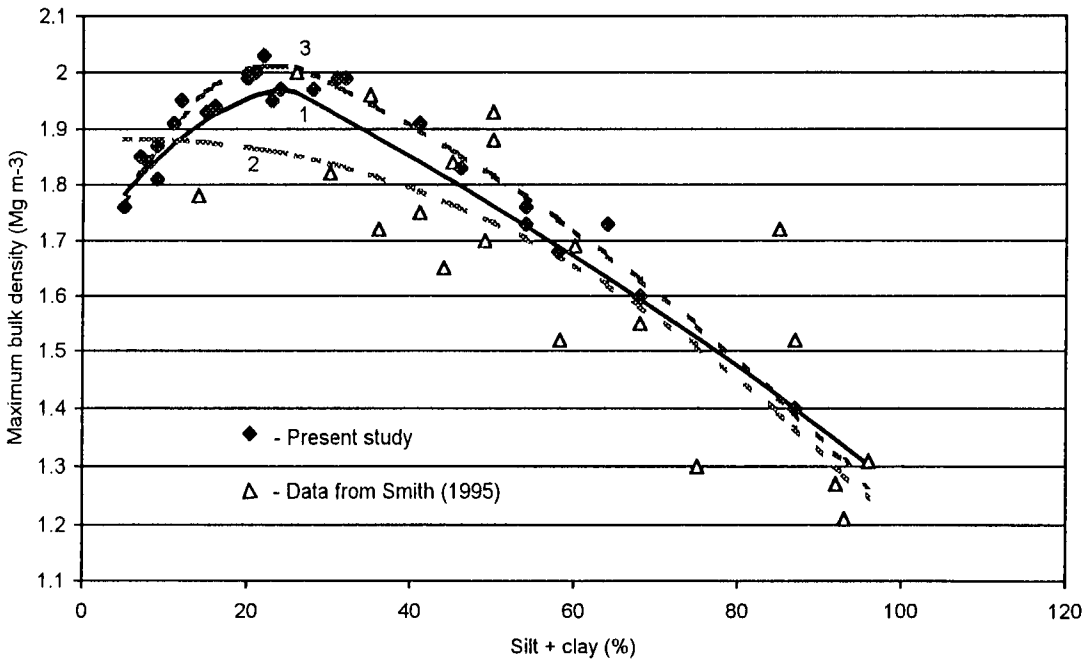
reach the highest maximum bulk density because there is sufficient space for the entrapment of small particles between the larger ones. It is recommended that Equation 3.11 can be used to predict the maximum bulk density of the South African soils:

S+C < 25%:

$$BD_{max}(Mg\ m^{-3}) = 1.6864 + 0.02133*(S+C\%) - 0.0004*(S+C\%)^2 \qquad R = 0.82 \quad (3.11a)$$

S+C > 25%:

$$BD_{max}(Mg\ m^{-3}) = 2.1527 + 0.00668*(S+C\%) - 0.000023*(S+C\%)^2 \qquad R = 0.87 \quad (3.11b)$$



1 - Combined data: Silt + clay < 25%: $Y = 1.6864 + 0.02133*(S+C) - 0.0004*(S+C)^2$ (R=0.82)
> 25%: $Y = 2.1527 - 0.00668*(S+C) - 0.000023*(S+C)^2$ (R=0.87)

2 - Data from Smith (1995): $Y = 1.8777 + 0.0011*(S+C) - 0.000088(S+C)^2$ (R=0.83)

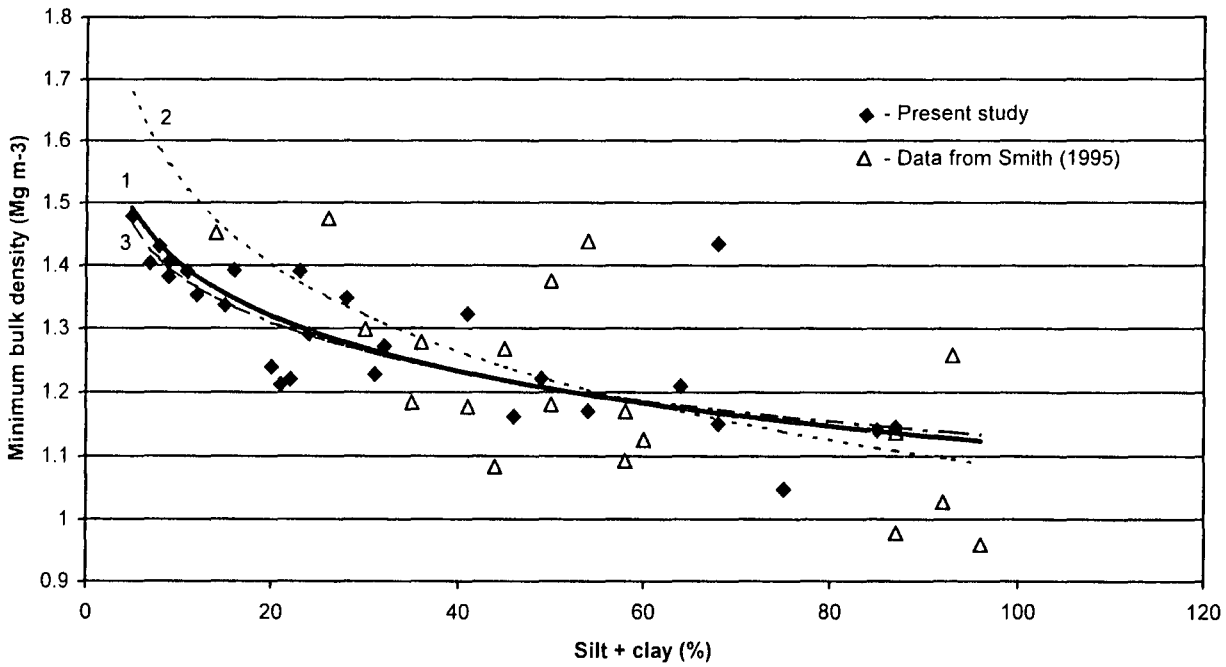
3 - From the study: Silt + clay<25%: $Y = 1.614+0.034991*(S+C)-0.00077*(S+C)^2$ (R=0.94)
Silt + clay>25%: $Y = 2.146-0.003788*(S+C)-0.000056*(S+C)^2$ (R=0.98)

Figure 3.11: Maximum bulk density predicted by silt plus clay for combined agricultural and forestry soils obtained by Smith (1995).

3.3.2 Minimum bulk density

The relationships between silt plus clay content and minimum bulk density are represented in the Figure 3.12. The graph labelled 2, representing the semi-logarithmic function fitted through the data points for the samples supplied by Smith, deviate from Graph 3 (present data set) and the graph labelled 1 (combined data set). The deviation becomes only significant for sandy soils as a result of insufficient data points. There is little difference between the graphs for the present and combined data sets. Thus, it is suggested that the minimum bulk density for South African soils can be estimated using the Equation 3.12.

$$BD_{min}\ (Mg\ m^{-3}) = 1.6925 - 0.1245 * \ln(S+C\%) \qquad R = 0.72 \qquad (3.12)$$



1 - Combined data: Y = 1.6925 - 0.1245*ln(S+C) r = 0.72

2 - Data from Smith (1995): Y = 1.9988 - 0.1993*ln(S+C) r = 0.60

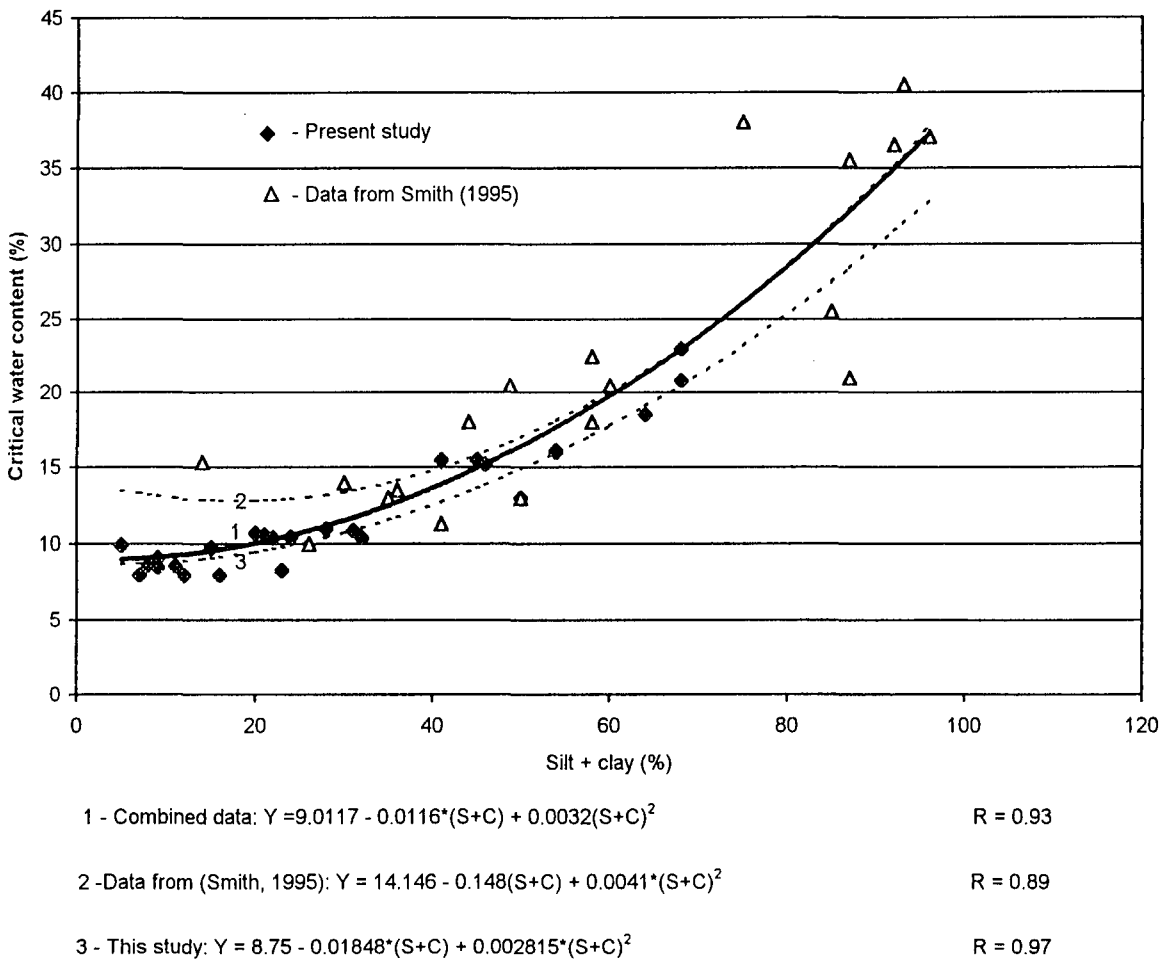
3 - From the study: Y = 1.642 - 0.11121*ln(S+C) r = 0.85

Figure 3.12: Minimum bulk density as function of silt plus clay for agricultural and forestry soils.

3.3.3 Critical water content

The relationship between silt plus clay and the optimum critical water content at which the maximum bulk densities were obtained are shown in Figure 3.13 for the different sets of data. The three graphs are remarkably similar and is suggested that the Equation 3.13 representing the combined data (graph labelled 1) be used for estimating the critical water content for soils in South Africa.

$$CWC\ (\%) = 9.0117 - 0.0116*(S+C\%) + 0.0032*(S+C\%)^2 \qquad R = 0.93 \qquad (3.13)$$



1 - Combined data: $Y = 9.0117 - 0.0116*(S+C) + 0.0032(S+C)^2$ R = 0.93

2 -Data from (Smith, 1995): $Y = 14.146 - 0.148(S+C) + 0.0041*(S+C)^2$ R = 0.89

3 - This study: $Y = 8.75 - 0.01848*(S+C) + 0.002815*(S+C)^2$ R = 0.97

Figure 3.13: Relationship between silt plus clay content and critical water content (including data from forestry soils, Smith, 1995).

3.4 Conclusions and summary

The main objective of this chapter was to determine the influence of texture and organic matter contents on the maximum and minimum bulk density, and on the critical water content for obtaining maximum compaction of the soils. The following conclusions can be stated:

- There is a good relationship between texture and organic matter content expressed as loss on ignition.

- Either texture or organic matter content can be used to predict the maximum and minimum bulk densities as well as the critical water content of the soils.

- The highest maximum bulk density is achieved at silt plus clay contents around 25%, or loss on ignition of 3.6%.

- Maximum bulk density can be used to predict the critical water content of the soils.

- The organic matter content of soils decreased the minimum bulk density because it has a lower density than the solid inorganic particles.

- The prediction of the maximum and minimum bulk densities of the cultivated soils in the Free State from easy to measure silt plus clay contents or organic matter contents should be valuable for assessing the effectiveness of soil tillage operations.

- Combination of the data obtained during this study with those reported for forestry soils (Smith, 1995) made it possible to derive equations for the prediction of the maximum and minimum bulk densities and critical water content with a more universal application.

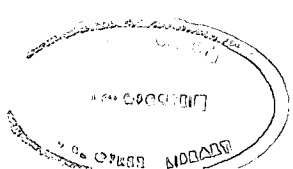
CHAPTER 4
THE RELATIVE BULK DENSITY CONCEPT

4.1 Introduction

The physical soil properties undergo changes when submitted to compaction forces (Freitag, 1971). The state of compaction at any time, may be measured in terms of void ratio, porosity, bulk density (Marsili & Servadio, 1996) and soil strength (Smith *et al.* 1997c). Soil dry bulk density and soil strength are usually used as indices of compaction (Ekwue & Stone, 1995).

Soil bulk density determines the mass for a specific volume. It is an easily measured physical parameter (Bodman & Constantin, 1965) and several soil management decisions can be made from the measured dry bulk density of the soil (Gupta & Larson, 1979). Da Silva *et al.* (1997) have stated that bulk density measurements are of limited value as an indicator of the effect of management on soil compaction when soils with different characteristics are compared. Similarly, Henderson *et al.* (1988) mentioned that a bulk density value alone is not a reliable indicator of potential problems with root penetration and air or water movement within the soil. Gupta & Larson (1979) stated that interpretations of bulk density values could be improved if soil particle size analysis could be used as a predictor of soil bulk density. Bennie and Burger (1988) cited Bennie & Burger (1979) who found that relative bulk density, expressed as the ratio between the bulk density and the maximum Proctor density, correlated better with penetrometer resistance than did either absolute bulk density or porosity. The relative bulk density is therefore a measure of the degree of compaction which can be used to compare compaction values among soils with different textures (Bennie & Burger, 1988).

The maximum bulk density may be used as a reference value to describe the degree of compactness of a soil (Smith *et al.*, 1997b). For instance, Van der Watt (1969) classified the degree of compaction based only on the maximum bulk density. However, it should



be noted that for each specific soil, the maximum bulk density will be determined by intrinsic properties, for example the texture.

According to Da Silva *et al.* (1997), Erikson *et al.* (1974) used the concept of relative compaction or relative bulk density to compare the response of different soils with a range of properties. The relative density of the soil (RD) was defined as the percentage of a current bulk density (BD) to a reference value (BD_{ref}), as shown in Equation 4.1. The reference value can be predicted from other soil properties (Da Silva *et al.* 1997).

$$RD = \frac{BD}{BD_{ref}} \tag{4.1}$$

Generally, the maximum bulk density (BD_{max}) obtained with the Proctor-test, as been used as the reference bulk density (Equation 4.2).

$$RD = \frac{BD}{BD_{max}} \tag{4.2}$$

Analyzing Equation 4.2 mathematically, it seems that the bulk density is assumed to vary from a maximum value to zero, which in natural conditions is not true. Other approaches were idealised by other researchers. Hakansson (1990) proposed a definition of relative density based on the ratio between the bulk density and the bulk density obtained by a standardized laboratory test under uniaxial stress of 200 kPa (BD_{200kPa}), Equation 4.3.

$$RD = \frac{BD}{BD_{(200\,Kpa)}} \tag{4.3}$$

Bennie & Van Antwerpen (1988) suggested another approach involving the maximum (BD_{max}) and the minimum (BD_{min}), bulk densities (Equation 4.4). According to their definition, the relative bulk density is the ratio between the current bulk density minus BD_{min} and the difference between the maximum and the minimum bulk densities.

$$RD = \frac{BD - BD_{min}}{BD_{max} - BD_{min}} \quad (4.4)$$

The range within which the bulk density can vary is taken as the reference value. This proposal includes a new concept, the minimum bulk density. This concept has been discussed in detail in Section 2.3.2. The minimum and maximum porosity represent the extremes of porosity between which each soil could be packed (Panayiotopoulos & Mullins, 1985). These extremes represent the maximum and minimum bulk densities, respectively. At the maximum bulk density all the voids spaces of bigger fractions are filled with particles from the small fraction whereas at the minimum bulk density, the void spaces are at a maximum (Gupta & Larson, 1979).

Another parameter widely used for many soil management decisions is the soil strength. 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). The measurement of this parameter is done to estimate the mechanical resistance experienced by root systems in compacted soils (Ayers & Perumpral, 1982 and Smith *et al.*, 1997c). According to Bradford (1986), any device designed to measure resistance to penetration may be called a penetrometer. A penetrometer measures the mechanical resistance sensed by a metal probe. This technique is commonly accepted (Smith, 1995). Penetrometer resistance can provide a rapid assessment of the strength of agricultural soils indicating the severity of soil compaction in the field (Elbanna & Witney, 1987; Henderson *et al.*, 1988 and Smith *et al.* 1997c). Many researchers have reported the usefulness of penetrometer measurements in agronomic, physiological and tillage research (Bennie & Burger, 1988 and Henderson *et al.*, 1988).

Mirreh & Ketcheson (1972) mentioned that the relationship between soil bulk density and water content renders the resistance behaviour of soils to be unpredictable unless it is related to both these parameters simultaneously. Bennie & Burger (1988) recommended that penetrometer readings should be taken at constant water content preferably at field water capacity. This is the widely accepted norm and is essentially a reference value

because it is very difficult to infer strength characteristics throughout the whole available water range from a simple measurement (Smith *et al.*, 1997c). Otherwise, a set of calibration curves and a multiple regression Equation relating penetrometer resistance to bulk density and water content, is needed for a meaningful interpretation of the measurements (Bennie & Burger, 1988).

An attempt will be made in this Chapter to establish threshold relative bulk density classes for assessing the root growth conditions in soils.

4.2 Threshold penetrometer resistance values

Sands *et al.*, (1979) and Bennie & Burger (1988) stated that for a specific soil, the penetration resistance, when measured at a standard reference water content, increases with increasing bulk density. Penetrometer resistance is strongly related to water content (Sands *et al.*, 1979). It may vary considerably throughout the year with wetting and drying cycles (Smith *et al.*, 1997c). It was decided that instead of field water capacity the critical water content, obtained from the maximum bulk density determinations (Section 3.2.4), would be considered as the standard reference water content for threshold penetrometer resistance values. Although the critical water content is lower than field water capacity, it is assumed that in cultivated fields the soils will be drier than field capacity for most of the time and the critical water content will be more representative of the average soil water content during the growing of crops.

It was also decided to develop threshold relative bulk density classes only for soils with silt plus clay contents less than 35% because more clayey soils develop structure. Penetrometer resistance measured with a rigid probe is a poor indicator of root growth conditions in structured soils because the flexible roots grow along the cracks.

For the determination of threshold penetrometer resistance values, the relationship between penetrometer resistance and root growth from Bennie (1991) was used as reference (Figure 4.1). Figure 4.1 shows the relationship between the relative root length

and penetrometer resistance for selected crops. At 0.5 MPa the root length can be about 100%; from 0.5 to 1.5 MPa, there is a sharp decrease in root length. Gupta & Allmaras (1987) found a similar behavior within the same range. At 3.0 MPa there is a very drastic

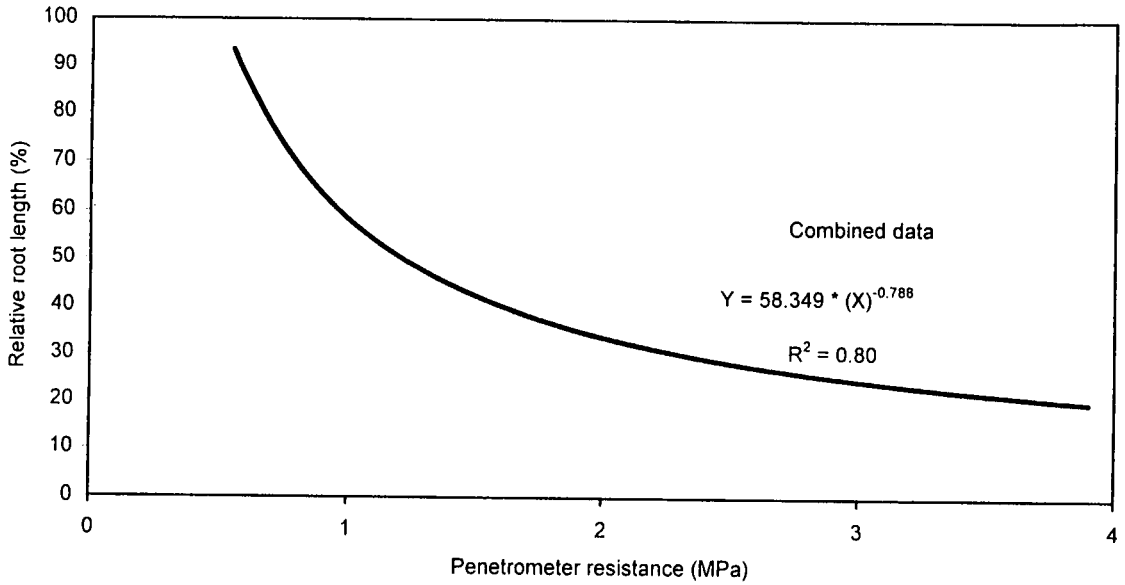


Figure 4.1: Relationship between the relative root length of 70-day-old maize, cotton, wheat, and groundnut plants and penetrometer resistance (Bennie, 1991).

reduction. The strength of 2.0 MPa which is considered by many authors as a standard critical penetrometer resistance value was considered as the beginning of high stress conditions. Gupta & Allmaras (1987) did not find tap roots of cotton in soils with penetrometer resistances of 2.0 MPa. These critical values were used to establish the penetrometer resistance classes presented in the Table 4.1

Table 4.1: Penetrometer resistance classes

Degree of compaction	Penetrometer resistance (MPa)
Loose	< 0.5
Moderate	0.5 – 1.5
Moderately high	1.5 – 2.0
High	2.0 – 3.0
Very high	>3.0

This guideline was developed with the assumptions that the penetrometer resistance in the mentioned classes will produce the following effects on root growth and crop development at the critical water content:

- < 0.5 MPa, the soil is too loose so that there is not enough soil-seed contact for good development;

- 0.5 – 1.5 MPa, is considered loose compaction and the soil has optimum strength for root growth of the majority of crops;

- 1.5 – 2.0 MPa, the penetrometer resistance is relatively high but roots of certain species can still develop well;

- 2.0.-3.0 MPa, many root crops cannot develop in this environment and the plants will be stressed;

- >3.0 MPa, roots of few crop species can survive under such condition.

4.3 Procedure for relating the penetrometer resistance classes to relative bulk density

The penetrometer resistance and bulk density values obtained during the compression index determinations for each soil, as described in Section 2.6 were used. All the curves relating penetrometer resistance to bulk density showed a logarithmic relationship (Appendix 4.1). Using regression analysis, Equations where determined for the relationships between penetrometer resistance as a dependent variable and bulk density (Equation 4.5).

$$Y = a + b * \log_{10}(X) \qquad (4.5)$$

Where: Y = penetrometer resistance (MPa)

a = intercept

b = slope

X = bulk density (Mg m^{-3})

The Equation 4.5 was converted to calculate the bulk densities corresponding to critical penetrometer resistance values of 0.5, 1.5, 2.0 and 3.0 MPa (Equation 4.6) for each soil.

$$X = 10^{\frac{Y-a}{b}} \tag{4.6}$$

Where: X – bulk density for the selected penetrometer resistance (Mg m^{-3})

Y - penetrometer resistance (Mpa)

a - intercept

b – slope

The maximum and minimum bulk density values needed for converting the bulk densities of each soil to relative densities with Equation 4.4 were calculated using Equations 3.4a and 3.6 and the corresponding silt plus clay contents. The averages and the standard deviations for the relative bulk densities for the different penetrometer resistance classes were calculated and presented in Tables 4.2 to 4.5.

There is generally an increase in standard deviation for the higher penetrometer resistance classes (Table 4.6), but the variation is sufficiently low to establish reasonably reliable threshold values for relative bulk density. The relative bulk density classes are given in Table 4.7. The threshold values in the different classes is slightly more conservative than those suggested by Bennie & Van Antwerpen (1988), shown in Table 4.8.

The relative bulk density of a soil can be calculated from the measured bulk density and the maximum and minimum bulk densities estimated from the silt plus clay percentage.

Table 4.2: Bulk density and relative density at 0.5 MPa

S+C(%)	BD_{max}	BD_{min}	$BD_{(PR=1.5)}$	$RD_{(PR=1.5)}$	Average	STD
5	1.77	1.46	1.48	0.07		
7	1.82	1.43	1.55	0.31		
8	1.84	1.41	1.53	0.27		
9	1.87	1.40	1.54	0.31		
9	1.87	1.40	1.53	0.29		
11	1.91	1.38	1.57	0.36		
12	1.92	1.37	1.58	0.38		
15	1.97	1.34	1.48	0.23		
16	1.98	1.33	1.53	0.30		
20	2.01	1.31	1.53	0.32		
21	2.01	1.30	1.56	0.37		
22	2.01	1.30	1.57	0.39		
23	2.01	1.29	1.46	0.23		
24	2.01	1.29	1.55	0.36		
28	2.01	1.27	1.49	0.30		
31	1.99	1.26	1.44	0.25		
32	1.97	1.26	1.47	0.30	0.30	0.076

Table 4.3: Bulk density and relative density at 1.5 MPa

S+C(%)	BD_{max}	BD_{min}	$BD_{(PR=1.5)}$	$RD_{(PR=1.5)}$	Average	STD
5	1.77	1.46	1.58	0.38		
7	1.82	1.43	1.64	0.55		
8	1.84	1.41	1.59	0.42		
9	1.87	1.40	1.62	0.48		
9	1.87	1.40	1.60	0.43		
11	1.91	1.38	1.63	0.48		
12	1.92	1.37	1.64	0.48		
15	1.97	1.34	1.53	0.31		
16	1.98	1.33	1.58	0.38		
20	2.01	1.31	1.58	0.38		
21	2.01	1.30	1.62	0.45		
22	2.01	1.30	1.61	0.44		
23	2.01	1.29	1.53	0.32		
24	2.01	1.29	1.59	0.42		
28	2.01	1.27	1.53	0.34		
31	1.99	1.26	1.47	0.29		
32	1.97	1.26	1.52	0.37	0.41	0.071

Table 4.4 Bulk density and relative density at 2.0 MPa

S+C(%)	BD_{max}	BD_{min}	$BD_{(PR=1.5)}$	$RD_{(PR=1.5)}$	Average	STD
5	1.77	1.46	1.63	0.54		
7	1.82	1.43	1.69	0.68		
8	1.84	1.41	1.63	0.50		
9	1.87	1.40	1.66	0.57		
9	1.87	1.40	1.64	0.51		
11	1.91	1.38	1.66	0.54		
12	1.92	1.37	1.67	0.54		
15	1.97	1.34	1.56	0.35		
16	1.98	1.33	1.60	0.41		
20	2.01	1.31	1.60	0.42		
21	2.01	1.30	1.65	0.49		
22	2.01	1.30	1.63	0.47		
23	2.01	1.29	1.56	0.37		
24	2.01	1.29	1.61	0.45		
28	2.01	1.27	1.54	0.37		
31	1.99	1.26	1.49	0.31		
32	1.97	1.26	1.54	0.40	0.47	0.094

Table 4.5: Bulk density and relative density at 3.0 MPa

S+C(%)	BD_{max}	BD_{min}	$BD_{(PR=1.5)}$	$RD_{(PR=1.5)}$	Average	STD
5	1.77	1.46	1.73	0.87		
7	1.82	1.43	1.80	0.94		
8	1.84	1.41	1.70	0.66		
9	1.87	1.40	1.75	0.75		
9	1.87	1.40	1.71	0.66		
11	1.91	1.38	1.73	0.67		
12	1.92	1.37	1.73	0.65		
15	1.97	1.34	1.61	0.44		
16	1.98	1.33	1.65	0.49		
20	2.01	1.31	1.65	0.48		
21	2.01	1.30	1.71	0.58		
22	2.01	1.30	1.67	0.53		
23	2.01	1.29	1.63	0.47		
24	2.01	1.29	1.66	0.51		
28	2.01	1.27	1.58	0.42		
31	1.99	1.26	1.52	0.35		
32	1.97	1.26	1.59	0.46	0.58	0.163

Table 4.6: Critical penetrometer resistance values and the average of the respective relative bulk densities.

Penetrometer resistance (MPa)	Relative density	
	Average	Standard deviation
0.5	0.30	0.075854
1.5	0.41	0.070617
2.0	0.47	0.093932
3.0	0.58	0.162593

The proposed relative bulk density classes (Table 4.7) and threshold values can then be used to evaluate the physical and mechanical condition of the soil in terms of root growth and degree of compaction.

Table 4.7: Threshold relative bulk density values (RD) and the corresponding critical penetrometer resistance values.

Degree of compactness	Critical penetrometer resistance values (MPa)	Threshold relative bulk density values
Very loose	< 0.5	<0.30
Loose	0.5 – 1.5	0.30 - 0.40
Moderately	1.5 – 2	0.40 – 0.50
Dense	2.0 – 3.0	0.50 - 0.60
Very dense	> 3.0	>0.60

Table 4.8: Threshold values proposed by Bennie & Van Antwerpen (1988)

Degree of compaction	Threshold bulk density values
Low	<0.5
Medium	0.5-0.6
High	0.6-0.7
Very high	>0.7

4.4 Conclusions

The objective of this chapter was to determine classes for the degree of compaction using the relative bulk density concept. These classes can be used to determine the degree of compactness of a soil when the bulk density and silt plus clay content are known. Relative density threshold values for the degree of compactness classes, ranging from loose to very dense, were determined. The relative density of a soil can therefore be used to determine the degree of compactness of looseness resulting from soil management actions.

CHAPTER 5
SOIL PROPERTIES AFFECTING COMPRESSIBILITY OF SOILS

5.1 Introduction

Soil compaction is the decrease in volume for a specific mass of soil. It is mainly caused by the propagation of stress through the soil medium due to forces applied at the soil surface (Block, Johnson, Bailey, Burt & Raper, 1994). The ease with which compaction occurs is called soil compressibility (Bradford & Gupta, 1986). The compactive response of a soil to externally applied forces is usually expressed in terms of change in bulk density, void ratio or total porosity. According to Soane (1990), Kuipers (1959) stated that there is a need to make compressibility results more meaningful, in terms of agricultural productivity.

Soil compressibility is influenced by external and internal factors. External factors comprise applied pressures either by agricultural equipment, animals or raindrops. Panayiotopoulos & Mullins (1985), mentioned a number of internal factors like organic matter content, water content, particle size distribution, median particle size, particle shape and surface roughness. Organic matter content, water content and particle size distribution are frequently used to assess many soil parameters and these properties are measured on a routine basis by most laboratories.

When the stress caused by wheels of agricultural equipment develops in the soil medium it is composed by vertical and lateral components. During the field operations, the lateral stress has a minor influence on soil compaction (Koolen, 1987 and Davidowski & Lerink, 1990). The soil compaction by field traffic can to a certain extent be simulated by the uniaxial test. In this test, the soil particles are only displaced vertically because the sample is confined in a steel cylinder, which is not the case under field conditions. O'sullivan (1992) cited Koolen & Vaandrager (1984) stating that the stress ratio in such tests may not differ much from values produced in the field. However, Smith *et al.*

(1997a) have mentioned that compaction in the field if often higher than in the uniaxial test with the same applied pressure. This may be attributed to the fact that compressive forces deriving from the movement of wheels and hoofs are dynamic.

When the bulk densities obtained with a range of predetermined stresses at a constant water content are plotted versus the logarithm of applied pressure the relationship will be linear over much of the applied stress range, Figure 1.1, (Larson *et al.*, 1980). The slope of the line is the compression index (Bradford & Gupta, 1986). These curves are used to compare basic compaction differences among agricultural soils (Larson *et al.*, 1980). Higher compression index values signify higher compressibility. This index can be influenced by the organic matter content, water content and texture.

Angers (1990) and Guerif (1990) found a decrease in compressibility due to higher organic matter contents. Similarly, according to Soane (1990), organic matter has a higher degree of elasticity under compression forces than do the mineral fraction. Similarly, Sommer & Zach (1992) found that a loamy sand soil, having a low organic matter content is more susceptible to compaction.

The soil water content at the time of compaction is the most important property affecting the compressibility (O'sullivan, 1992; Smith, 1995 and Etana *et al.*, 1997). Scholefield *et al.* (1985) stated that farmers must rely upon knowledge of the relationship between water content of the soil and its compressibility to guide grazing management. This is because the water content determines the forces that resist compaction (Koolen, 1987). The water has a lubrication effect when the soil is relatively dry (Felt, 1965 and Mckyes, 1985). If the voids are nearly or completely filled with water, very little or no volume change will take place immediately upon the application of a load, leading to low compressibility (Bradford & Gupta, 1986 and Smith *et al.*, 1997a). The water is virtually incompressible and where the water content is increased beyond the critical level required to obtain the maximum density, the excess water in the soil pores prevents the movement of soil particles (Felt, 1965).

Larson *et al.*, (1980) presented regression equations relating compression index to clay content for a range of temperate and tropical soils. The compression index does not show much difference between soils of the same texture from both climatic regions. Gupta & Allmaras (1987) found an increase in compression indices with increasing clay content up to 33% clay beyond which it levelled off. Smith *et al.* (1997b) found a similar relationship with a boundary clay content value of 35%. Angers (1990) considered soil with clay contents less than 35% as sandy where the clay content correlated well with compression index. For soils with high clay contents (> 35%), the compression index correlated better with organic matter.

The porosity and frictional forces of soils are related to texture. In general, soils with high porosities are more compressible than those with low porosity (Harris, 1971). Sandy soils have lower porosities and are less compressible than more finely textured soils characterised by higher porosities. The very coarse textured soils have high initial bulk densities, relatively to their maximum bulk densities, and the frictional forces dominate the soils resistance to compression and consequently the compressibility is low (Smith *et al.*, 1997b). Increasing the clay content to approximately 35% reduces the magnitude of the frictional forces resisting compression of soils, combined with an increase in porosity, the soils are more susceptible to undergo volume reduction under applied pressure. But, at higher clay contents, which correspond to poorly graded soils, the compressibility declines probably due to an uneven distribution of particle sizes and the soil particles cannot be forced into the smaller pores (Harris, 1971 and Panayitopoulos & Mullins, 1985). This is the reason why soils with a wider particle size distribution has a greater potential for developing a restricting pan (Gupta & Larson, 1979).

In this chapter, relationships between soil compressibility, organic matter content and texture are addressed.

5.2 Results and discussion

The compression tests were conducted at a constant water content equal to the critical water content needed to obtain the maximum bulk density. The critical water content is generally similar to the optimum water content for maximum compressibility (Table 5.1).

The complete set of graphs is given in appendix 5.1. The slope of only the linear part of the bulk density versus the logarithm of the applied pressure curve was used to calculate the compression index (Section 2.5). The relationship between compression index and silt plus clay content or organic matter content (loss on ignition) are shown in Figures 5.1 and 5.2, respectively. To make the results of this study comparable with other studies, the relationship between clay content and compression index (C) is also presented in Figure 5.3.

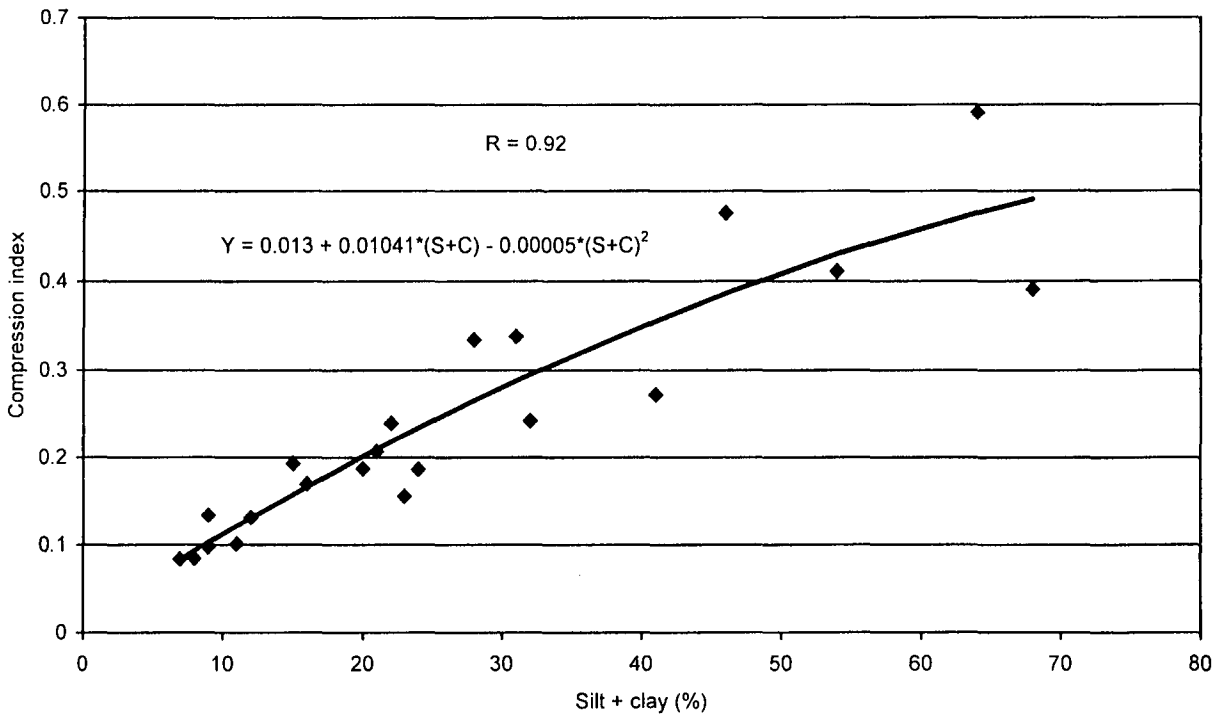


Figure 5.1 Silt plus clay content as a predictor of compression index.

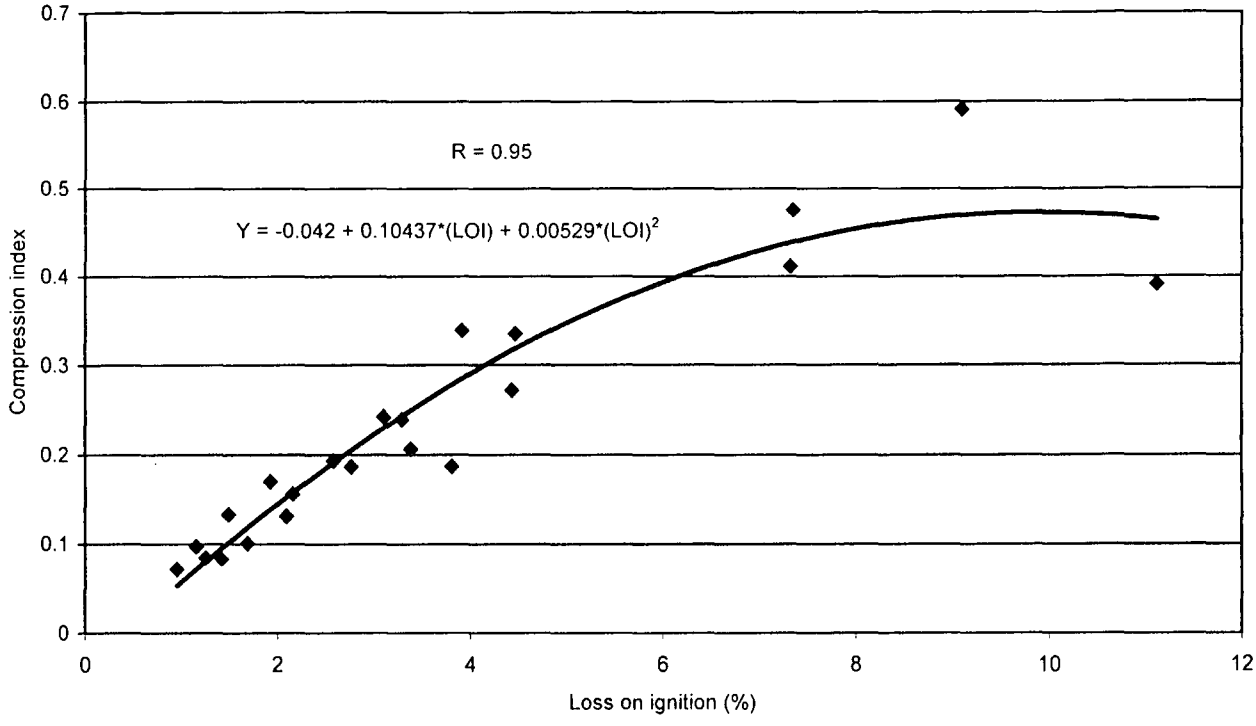


Figure 5.2: Compression index as a function of loss on ignition.

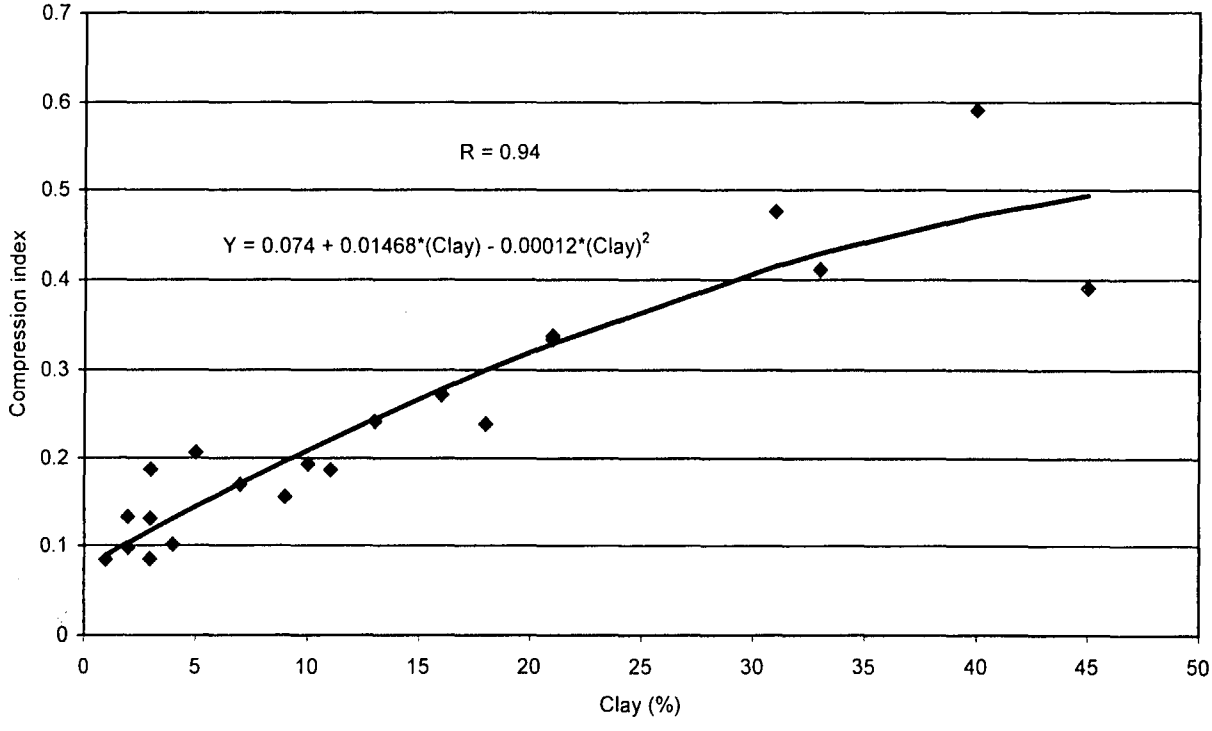


Figure 5.3: Relationship between clay content and compression index.

From Figures 5.1 and 5.2 it is clear that the relationships between compression index and silt plus clay or loss on ignition are similar. This should be expected as was shown in Section 3.2 there is a good relationship between silt plus clay and loss on ignition, meaning that these properties are interdependent. Figure 5.3 shows that it is difficult to confirm whether the threshold values of 33% found by Larson *et al.*, (1980) and Gupta & Allmaras (1987) and 35% by Angers (1990) and Smith *et al.* (1997b) will be applicable for the soils used in this study. The reason for the absence of a clear point of inflection is that there are only two samples with clay contents higher than 35% and the variation between them is large.

The prediction of compression index (CI) can be done using Equation 5.1 for silt plus clay, Equation 5.2 for loss on ignition or Equation 5.3 for the clay content.

$$CI = 0.013 + 0.01041*(S+C\%) + 0.00005*(S+C\%)^2 \qquad R = 0.93 \qquad (5.1)$$

$$CI = -0.042 + 0.10437*(LOI\%) + 0.00529*(LOI\%)^2 \qquad R = 0.95 \qquad (5.2)$$

$$CI = 0.074 + 0.01468*(Clay\%) + 0.00012*(Clay\%)^2 \qquad R = 0.94 \qquad (5.3)$$

These equations are only valid for the prediction of the CI for uniaxial loads varying between 200 and 1800 kPa.

The clay content also seems to be a good indicator of soil compressibility. In general, the compression indices from this study are slightly lower when compared at the same clay contents with the results found by other authors (Larson *et al.*, 1980; Gupta & Allmaras, 1987; Angers, 1990 and Smith *et al.*, 1997b). The reason could be that the critical water content, determined under impact with the Proctor test, used in this study probably exceeded the required optimum water content for maximum compression with the more gentle uniaxial test.

A regression analysis was performed to determine if the intercept values from the different Virgin Compression Curves are related to silt plus clay content. This relationship is shown in Figure 5.4. According to Figure 5.4, there is a clear linear relationship between these soil properties and it is represented by the Equation 5.4.

$$\text{Intercept} = 1.5374 - 0.0216*(S+C\%) \qquad r = 0.94 \qquad (5.4)$$

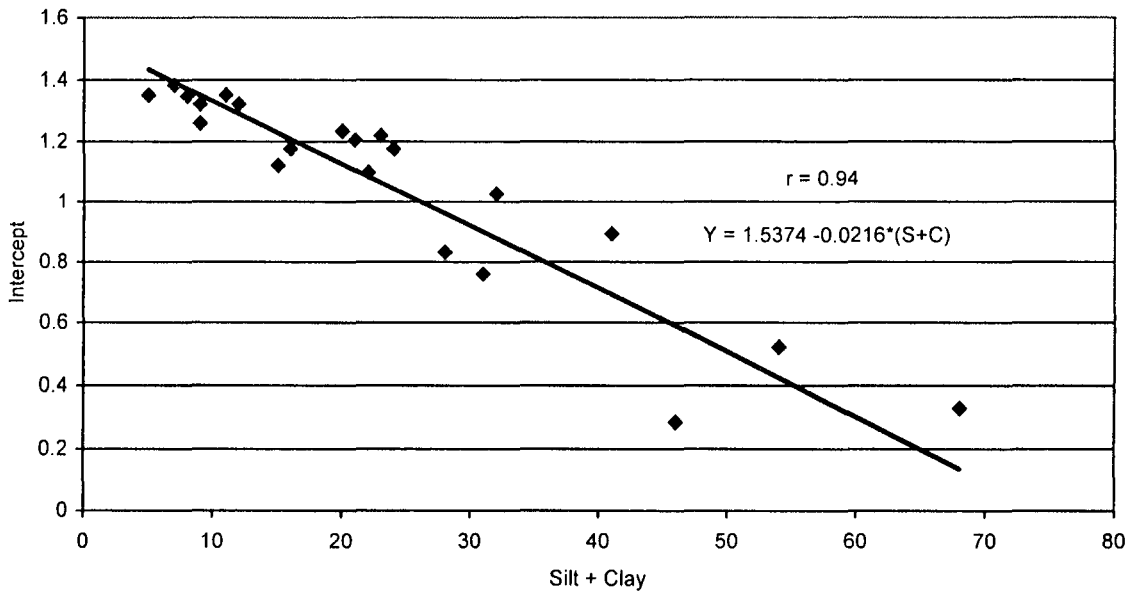


Figure 5.4: Intercept in the Virgin Compression Line predicted by silt plus clay content.

It was expected that the intercept values would be equal to the minimum bulk densities but can be seen in Figure 5.5 that the minimum bulk densities are relatively higher than the correspondent intercepts obtained from the uniaxial compression tests. The hypothesis is therefore false.

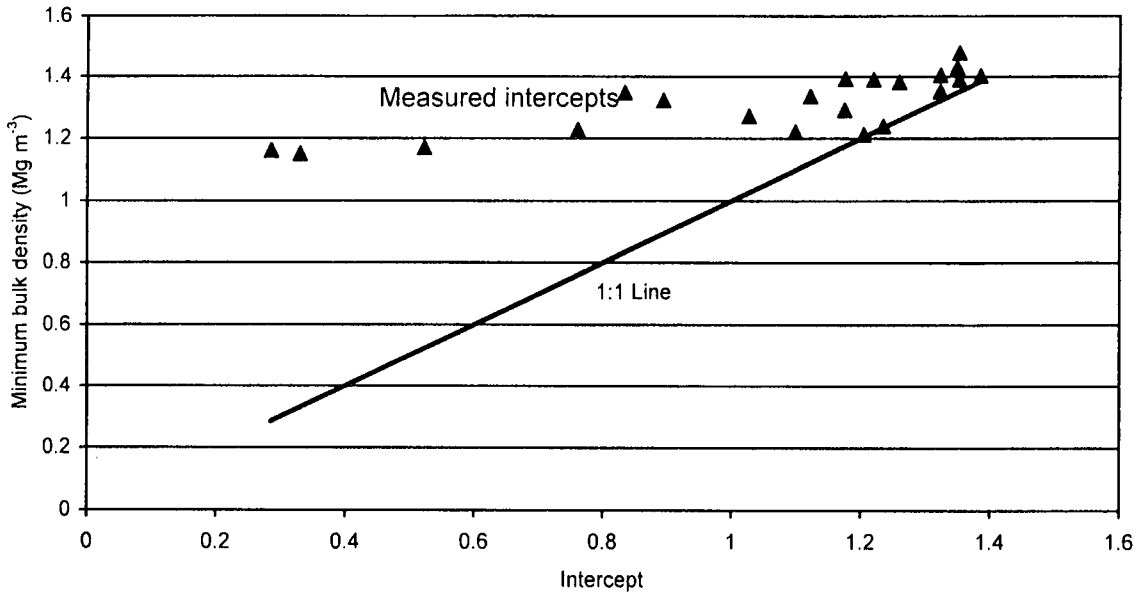


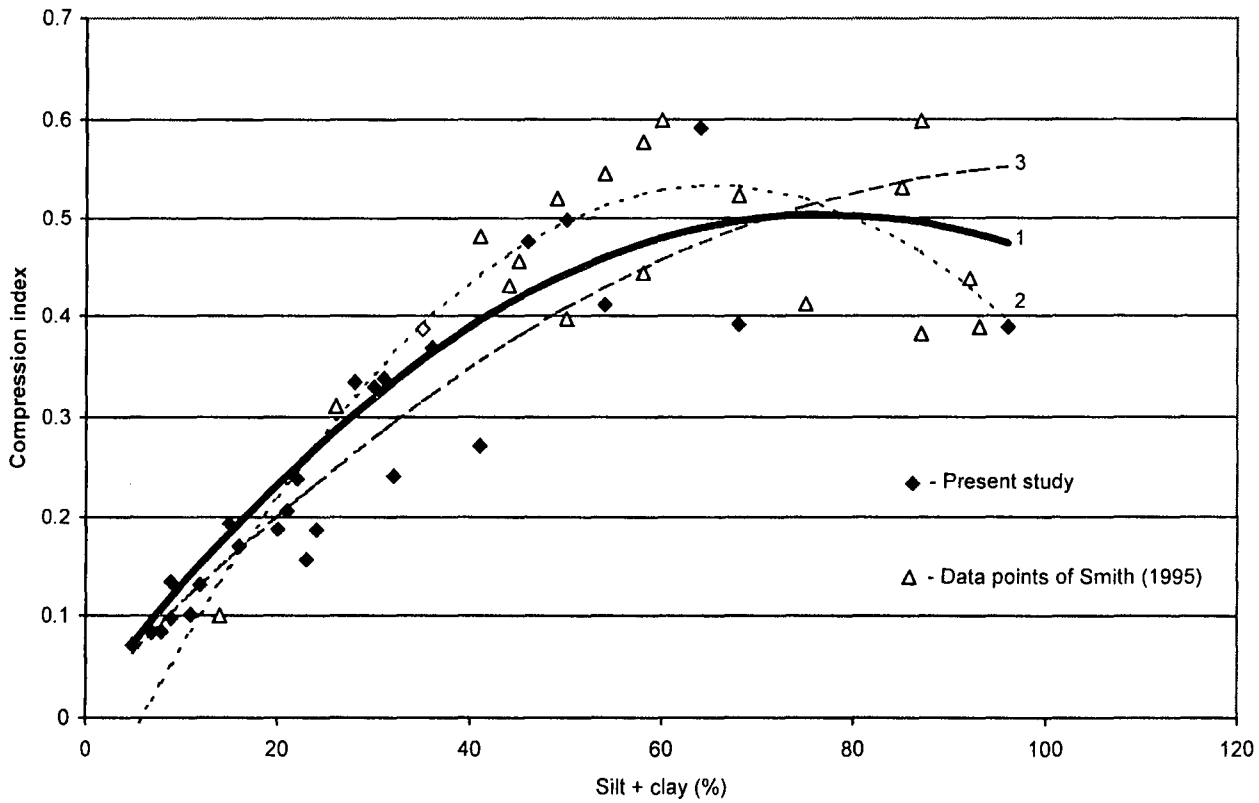
Figure 5.5: Deviation of the minimum bulk density from the calculated intercepts.

5.3 Comparison of the current results with the results from forestry soils

To be able to produce more meaningful conclusions the compression index values obtained in this study were compared with the ones found for forestry soils by Smith (1995). The results of this comparison are shown in the Figure 5.6. The graph labelled 2 was plotted using the results from the forestry soils whereas the graph labelled 3 are agricultural ones from this study. During the study of the forestry soils, Smith (1995) found that the critical water content for determining the maximum bulk density was generally higher than the critical water content for the compression index. From a comparison of the data (Table 5.1) it can be seen that the average difference is about 3% which was assumed acceptable for the purpose of this comparison.

The data from forestry soils, included in this comparison, are predominantly fine-textured soils while the agricultural soils are mainly coarse textured. These differences in the textural composition of the two data sets is the likely reason for the difference between the graphs. The relationship for the forestry soils shows a clear point of inflection compared to the one for the agricultural soils because it represents a relatively more evenly distributed silt plus clay range. The highest correlation coefficient was obtained

when a line was fitted using the combined data set (labelled 1, Figure 5.6). Since most of the forestry soils are from high rainfall areas and the agricultural ones from semi-arid regions one can expect a large variability in clay mineralogy. According to the relatively small degree of scattering, it seems that the clay mineral type might have a minor effect on the compressibility of the soils. Gupta & Allmaras (1987) came to a similar conclusion. All the graphs show lower compression indices at low silt plus clay contents. This observation confirms that the more sandy the soils are, the greater are the friction forces that create resistance to compression. Consequently, the ease with which sandy soils can be compressed is lower.



1 - Combined data: $Y = 0.01+0.01283*(S+C)-0.0000833*(S+C)^2$ R = 0.93

2 - Forestry soils (Smith, 1995): $Y = -0.113 + 0.019695*(S+C) - 0.00015*(S+C)^2$ R = 0.81

3 - From the study: $Y = 0.013 + 0.01041*(S+C) - 0.00005*(S+C)^2$ R = 0.92

Figure 5.6: Compression index from the combined data, including forestry soils (Smith, 1995).

Once the clay content increases, there is an increase in porosity and a reduction of the frictional forces resisting compression (Smith *et al.*, 1997b). At high silt plus clay contents, the compression indices reduce again because of the small particles and the difficulty with which the particles move into the micro pores during compression.

Table5.1: Critical water content for maximum bulk density and maximum compression indices (Smith, 1995)

Sample	CWC(BD_{max})	CWC(C_{max})	Difference	Difference(%)	Average(%)
1A	0.23	0.19	0.04	4	
2A	0.14	0.16	-0.02	-2	
2E	0.1	0.07	0.03	3	
3A	0.18	0.16	0.02	2	
4A	0.405	0.32	0.085	8.5	
5A	0.155	0.15	0.005	0.5	
6A	0.37	0.36	0.01	1	
6B	0.38	0.3	0.08	8	
6B2	0.355	0.35	0.005	0.5	
7A	0.35	0.23	0.12	12	
8A	0.255	0.2	0.055	5.5	
8B	0.21	0.14	0.07	7	
9A	0.205	0.09	0.115	11.5	
10A	0.13	0.14	-0.01	-1	
11A	0.128	0.14	-0.012	-1.2	
12A	0.153	0.13	0.023	2.3	
13A	0.085	0.14	-0.055	-5.5	
14A	0.125	0.12	0.005	0.5	
15A	0.18	0.11	0.07	7	
16A	0.155	0.13	0.025	2.5	
17A	0.135	0.08	0.055	5.5	
17B	0.13	0.09	0.04	4	
18A	0.18	0.13	0.05	5	
19A	0.365	0.24	0.125	12.5	
20A	0.13	0.12	0.01	1	
20B	0.15	0.13	0.02	2	
21A	0.225	0.2	0.025	2.5	
21B	0.15	0.15	0	0	
22A	0.13	0.13	0	0	
22B	0.205	0.2	0.005	0.5	
23A	0.16	0.16	0	0	
24A	0.16	0.13	0.03	3	
24B	0.165	0.14	0.025	2.5	
25A	0.21	0.16	0.05	5	
26A	0.23	0.19	0.04	4	3

5.4 Conclusions

The aim of this chapter was to investigate whether the more easily measured soil properties, organic matter and texture could be used to predict the compressibility of the soils studied. From the results presented in the Section 5.2, it can be concluded that either silt plus clay content, loss on ignition or clay content are reliable predictors of compression index (CI). The second order polynomial relationships between compression index and these soil properties have good correlation coefficients. From a comparison of the data of the current study with those from a study for forestry soils by Smith (1995), it can be concluded that regardless the clay mineral type, the compression index for South African soils can be estimated from the silt plus clay contents using the following equation:

$$CI = 0.01 + 0.01283*(S+C\%) - 0.0000833*(S+C\%)^2 \quad (5.5)$$

This equation is only valid for the prediction of the compression index for uniaxial loads between 200 and 1800 kPa where Equation 5.6 is used to estimate the bulk density of soils at different uniaxial loads at the critical water content (Equations 3.8 and 3.9).

$$BD = I + CI*\log_{10}UL \quad (5.6)$$

Where BD – dry bulk density (Kg m^{-3})
I – intercept estimated with Equation 5.4.
CI – compression index estimated with Equation 5.5
UL – uniaxial load (kPa)

No relationship between the intercept of the Virgin Compression Line and the minimum bulk density could be found. It is expected that there might be a relationship, and this aspect could be a worthwhile topic for future research.

CHAPTER 6
EVALUATING THE COMPACTIBILITY AND COMPRESSIBILITY OF SOILS FOR DIFFERENT PURPOSES

6.1 Introduction

The susceptibility of soils to compaction is dependent on several soil properties. From the previous chapters it can be concluded that compactibility and compressibility of the soils can be predicted from texture (silt plus clay content) and organic matter.

The widely used concept of compactibility is defined by Bradford & Gupta (1986) as the maximum density to which a soil can be packed by a given amount of energy. It only takes into consideration a single bulk density value but not the range over which the bulk density can vary. The problem with this definition is that, if two soils with equal maximum bulk densities but distributed on both sides of the critical point (silt + clay = 25%, Figure 3.4) are compared, it might give the impression that their compactibilities are similar while they are not. They will have different physical properties, different minimum bulk densities and consequently the range within which the bulk density can vary will be different. The concept of minimum bulk density may minimise this problem.

Taking into consideration the minimum bulk density concept it is proposed that the compactibility should be defined as the difference between the maximum and the minimum bulk densities of a soil, meaning that soils with equal maximum bulk densities but different minimum bulk densities will have different compactibilities. However, compactibility alone does not describe the susceptibilities of soils to compaction when subjected to a load. This problem can be addressed when compressibility is also taken into consideration. Compressibility is defined as the ease with which a soil can reduce its volume when subjected to a certain load (Bradford & Gupta, 1986).

Smith (1995) combined compactibility, using its classic concept, with compressibility, organic carbon and silt plus clay content to classify soils according to their susceptibility to compaction. For the current study, compactibility and compressibility where used in combination to assess the compaction susceptibility of soils.

6.2 Soil compactibility

Figure 6.1 shows the extremes between which the bulk densities of soils can vary ranging from the loose to compacted states presented by minimum and maximum bulk densities, respectively. Figure 6.2 illustrates the compactibility of the soils based on the revised definition (Section 6.1). From Figure 6.1 it can be noticed that for sandy soils, with lower silt plus clay contents, the range between the minimum and the maximum bulk density is comparatively narrower. This behaviour may be attributed to the low clay and organic matter contents of these soils. The sand has a higher density compared to organic matter. These soils are normally well sorted, comprising mineral grains with larger diameters than the pores into which the particles would have to be pressed during compaction. Consequently, the initial (minimum) bulk density of sandy soils is relatively high compared to its maximum (Smith, 1995). With an increasing amount of finer particles (silt plus clay), these particles fit into the larger pores and there is an increase in the bulk density. This increase reaches a maximum with an optimal mixture at about 25% silt plus clay, where the difference between the maximum and minimum bulk density reaches its maximum value. It represents the well-graded soils beyond which a reduction in compactibility will occur. The reduction is due to a progressive increase of the ratio between the small and large particles leading again to well sorted soils in which particles do not fit easily into the pore spaces. The increase in compactibility from the most sandy soils to the optimum value is sharper compared to the decrease beyond this value.

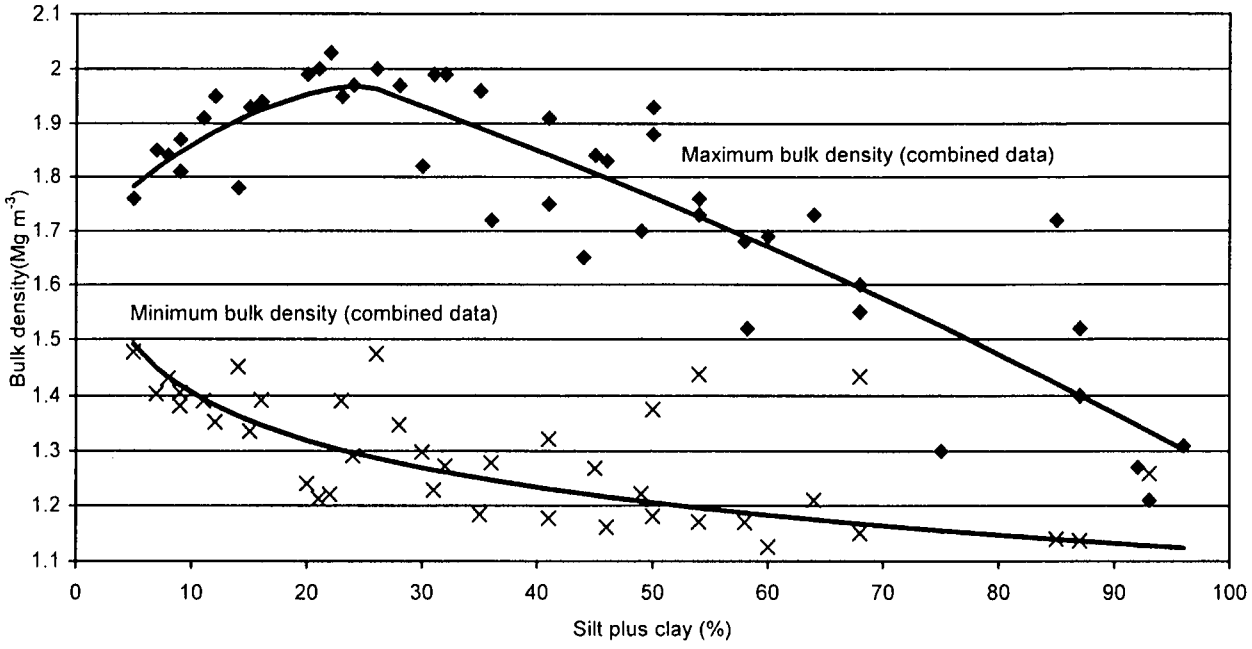


Figure 6.1 Maximum and minimum bulk densities variation as function of silt plus Clay contents (Equations for the maximum and minimum bulk densities to be found in the Figures 3.11 and 3.12 respectively)

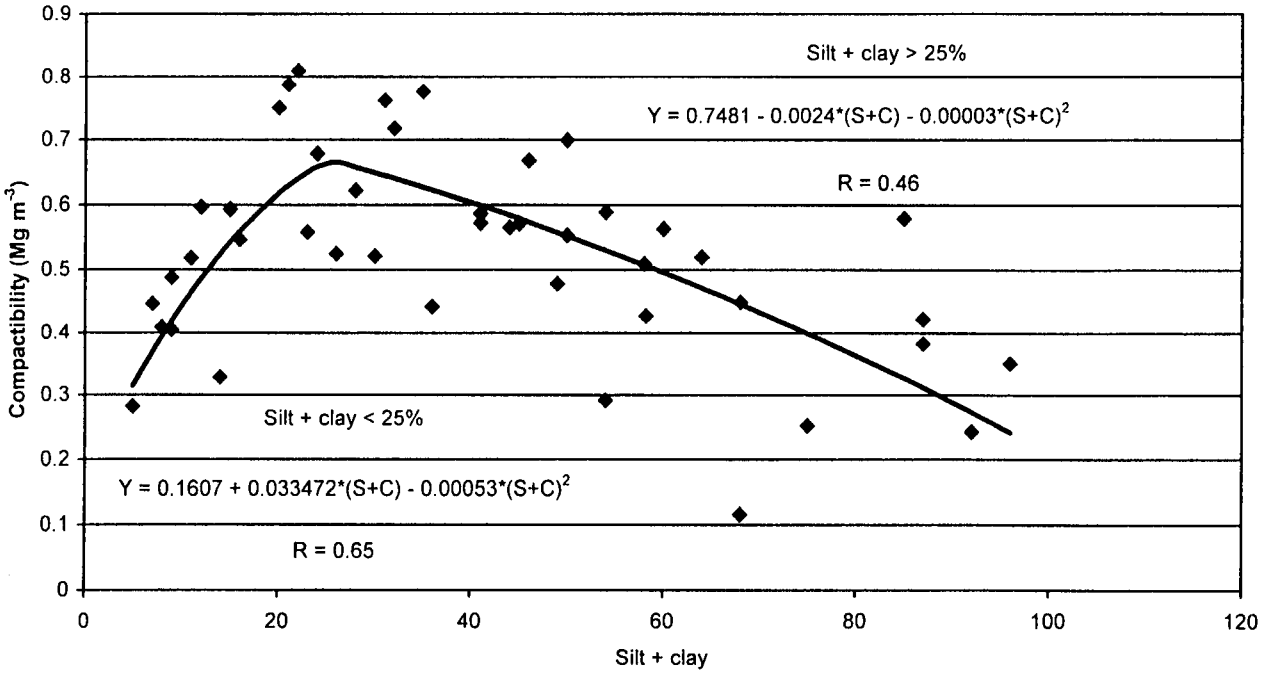


Figure 6.2 Relationship between silt plus clay contents and compactibility (difference between the maximum and minimum densities).

6.3 Compressibility of the soils

In order to study the range in compressibility, the amount of uniaxial load required to compress the soil to reach the bulk density critical for root growth was calculated. The calculation was based on the maximum and minimum bulk densities, threshold relative bulk density values for the different classes of compaction proposed in Table 4.7, the compression index and the intercept of the Virgin Compression Line (Equation 5.4). Equation 5.4 was derived from the soils included in the current study. This equation was used because the intercept values for the study of Smith (1995) were not available. The calculations of compressibility is aimed mainly at soils with silt plus clay contents less than 35%, which relates to the range of soils predominantly covered by the present study. The calculation was done in two steps. First, the critical density was calculated using Equation 6.1. The uniaxial loads required to compact the soil to the critical densities (CD) were calculated using the Equation 6.2. Finally a silt plus clay versus uniaxial load graph was plotted. Figure 6.3

$$CD = BD_{min} + (BD_{max} - BD_{min}) * 0.6 \quad (6.1)$$

Where: CD – critical density (Mg m^{-3})

BD_{min} – minimum bulk density (Mg m^{-3})

BD_{max} - maximum bulk density (Mg m^{-3})

0.6 – conversion factor to obtain the bulk density corresponding to very dense soil (Table 4.7).

$$UL = 10^{\left(\frac{CD-I}{CI}\right)} \quad (6.2)$$

Where: UL - uniaxial compression required to compact the soil to the critical density (kPa)

CD - critical density (Mg m^{-3})

I – intercept

CI – compression index

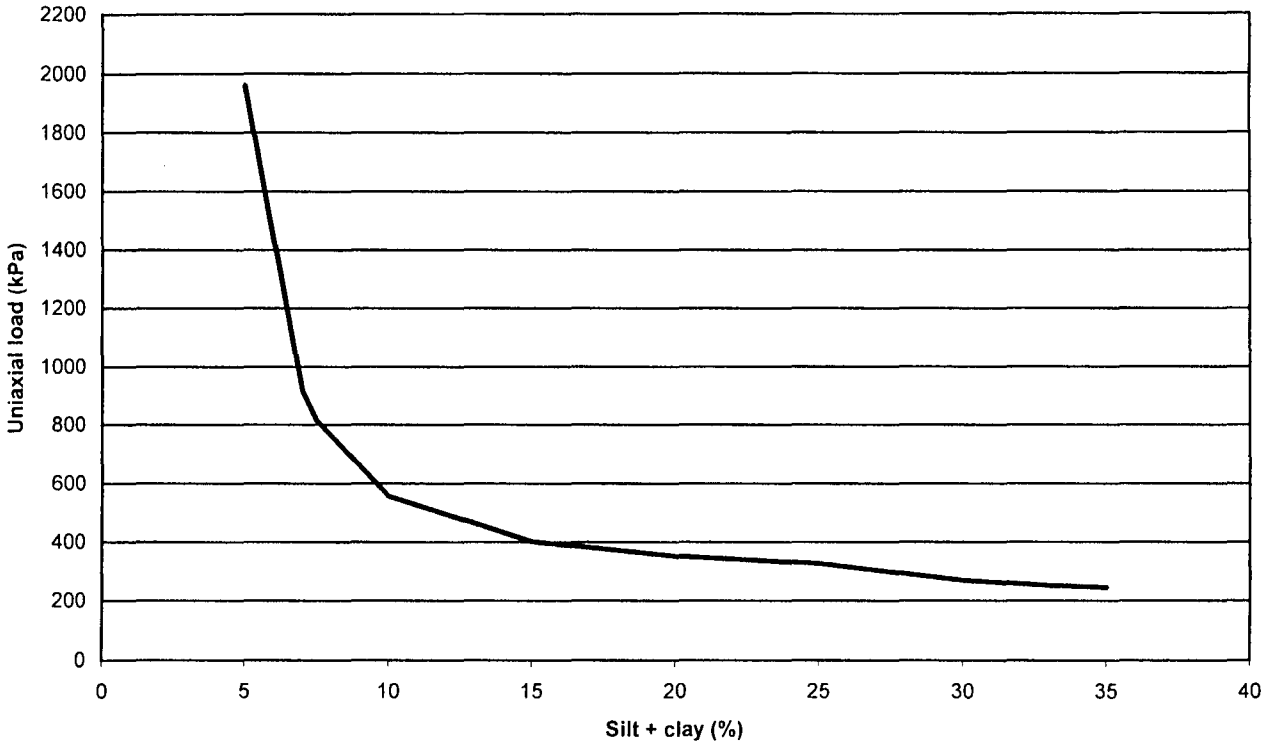


Figure 6.3: Uniaxial load required to compact the soils to the critical bulk densities at the critical water content.

shows that generally, with increasing silt plus clay contents, there is a decrease in the amount of load required to compact the soils to achieve very dense conditions at the critical bulk density at the critical water content for compaction. From Figure 6.3, some threshold silt plus clay values can be identified and interpreted in the following way:

0 – 5 % Silt + clay: Soils are very rigid with a high resistance to compression resulting in very high load requirements to obtain compacted conditions.

5 – 7 % Silt + clay: Rigid soils with a low compressibility requiring high uniaxial loads to compact at the critical water content.

5 – 10 % Silt + clay: These soils have a very low compressibility. Sharp decrease in the load requirements due to a considerable increase in compressibility resulting from an increase in the amount of finer particles. These particles reduce the frictional forces between the larger ones. Moderately compressible soils.

10 – 15% Silt + clay: The influence of the finer particles becomes more prominent by increasing the compressibility and in decreasing the compactive load required to reach the critical bulk densities. This may be due to an increase in the sliding effects promoted by the smaller particles. Highly compressible soils.

15 – 35% Silt + clay: The ease with which the soil can be compressed and deformed is very high. Consequently, the uniaxial load to reach the critical density is relatively low. Very highly compressible soils.

> 35% Silt + clay: Structured soils

6.4 Susceptibility of soils to compaction.

Based on the discussion in Sections 6.2 and 6.3 it can be stated that to assess the compaction susceptibility of soils the two major indicators are compactibility and compressibility. From Figures 6.2 and 6.3 the following interpretation can be made. The most sandy soils, have both low compactibility and compressibility, meaning that they are less susceptible to volume change because the compactive load requirement is very high. While the compressibility increases with increasing silt plus clay, the compactibility increases up to a critical value of silt plus clay around 25% after which it decreases.

The same threshold values used for the relative bulk density were also applied for assessing compactibility to classify the soils according to their susceptibility to compaction (Table 6.1).

Table 6.1: Threshold values of different parameters to assess the soil compaction susceptibility.

Degree of susceptibility to compaction	Silt plus clay (%)	Compactibility (Mg m^{-3})	Compressibility	Uniaxial load requirement (Kpa)
Very low	< 5	< 0.3 (Very low)	Very low	> 2000
Low	5 – 7	0.3 – 0.4 (Low)	Low	1000– 2000
Moderate	7 – 10	0.4 – 0.5 (Moderate)	Moderate	600 – 1000
High	10 – 15	0.5 – 0.6 (High)	High	400 – 600
Very high	15 - 35	>0.6 (Very high)	Very high	< 400
-	>35	Structured soils		

6.4.1 Engineering purposes

Engineering applications of soils includes their use for construction of houses, dams, roads, irrigation, drainage schemes, etc. As the study deals with susceptibility to compaction, which is mainly related to the effect of external forces on compactibility and compressibility, the interpretation will be limited only to construction of houses and roads.

Soil under houses or roads are submitted to heavy loads in dry and wet conditions. Therefore, soils on which the houses and/or roads have to be constructed, should be firm to resist deformation under dry and wet conditions. Very sandy soils, can resist deformation in dry and wet conditions regarded that there is no vibration. Once vibration is involved, the compressibility and sliding of the same soils increases and they might no longer be stable. Soils with a higher percentage of finer particles are very stable when dry but easily compressible under wet conditions and are thus not suitable for housing and road construction. These soils are well-sorted or poorly graded, meaning that they are composed of a large amount of small particles or similar size. Well-graded soils with silt plus clay around 25% are the most suitable for such engineering activities. They are composed of particles of a wide range of sizes increasing the number of contacts between the particles. They can be compacted to a dense stable state with the minimum compactive effort.

6.4.2 Trafficability of wet soils

It is important to understand the trafficability of wet soils because they are normally subjected to traffic by animals and machines during the agricultural activities. The following interpretations are based on the assumptions that we are dealing with uncompacted agricultural soils.

The trafficability is considered good when the soil can withstand external loads. Soils have a good trafficability when it is difficult to deform them which reduces the strain and the slip of the traffic wheels or hoofs of the animals. Although Figure 6.3 is based only on vertical static uniaxial compression pressure it gives us a good basis for monitoring the trafficability of wet soils. In Chapter 7 a more detailed discussion is presented where the critical compression values are compared to the ones mentioned by several studies, and suggestions are made to minimise the effect of loads on the soil.

Based on the analysis of compactibility and compressibility it can be stated that, when soils are near the critical water content, soils with silt plus clay contents less than 10%

can be trafficked with less risk of sinking wheels or animal hoofs. Once the texture of the soils become finer due to an increase in the portion of silt plus clay, the risk of sinkage increases because of the increase in compressibility of the soils. The trafficability of soils with silt plus clay contents between 10 and 25% at critical water contents decreases with increasing silt plus clay contents. Soils with silt plus clay contents of more than 25% offer bad conditions for trafficability when cultivated and loose. This is due to their increasing compressibility.

6.5 Conclusions

The aim of evaluating the revised definition of compactibility and compressibility of soils was to determine how the reaction of the soil when submitted to external forces can be predicted and to produce recommendations for an applicable use and management. The revised definition of compactibility seems to be a good contribution for assessing the soil behaviour under compression forces, specially when combined with compressibility. The susceptibility to compaction of apedal soils (silt plus clay < 35%), at the critical water content, increases from most sandy soils to soils with higher amounts of finer particles. Well-graded soils, with silt plus clay contents close to 25%, are the most suitable for engineering purposes. The soils with silt plus clay contents between 15 and 35% are suitable for engineering purposes but are also very susceptible to excessive compaction. The susceptibility to compaction can be classified in five (5) classes varying from very low to very high.

CHAPTER 7
SUMMARY AND CONCLUSIONS

The main objectives of this research were to determine the relationship between easily measured soil properties and compaction, compactibility and compressibility of soils. The relationships should be useful to distinguish between the beneficial and excessive degree of compaction. The second objective was to propose a procedure for the prediction and classification of the susceptibility of soils to compaction especially for the Free State. The third objective was to compare the results of the current study from a semi-arid climate with results obtained for forestry soils under more humid conditions.

Twenty two soil samples with silt plus clay contents varying between 4 and 68% but with majority being more sandy , were collected from different sites in the Free State Province.

The soil water content, particle size distribution and organic matter content were found to be factors which determine the behaviour of soils when submitted to an external load. These findings confirm the statements of Bingner & Wells (1992) and Bennie & Botha (1986). Water films increase particle mobility (McKyes, 1985), the soil mineral particles form a matrix which resists deformation by external forces (Guerif, 1990) and the organic matter acts as a buffer to reduce compaction effects (Spivey *et al.*, 1986 and Ekwe, 1990).

It was found from the current study and others (Felt, 1965; Harris, 1971; Guerif, 1990; Wagner *et al.*, 1994; Etana *et al.*, 1994; Ekwe & Stone, 1995 & Smith *et al.*, 1997b) that the bulk density of soils increases under impact load to a maximum value after which it decreases again. This is because with an increase in water content there is an increased lubrication activity by the water facilitating the packing of soil particles. The amount of water in the soil at which the maximum bulk density is obtained is called the critical water content (Saini, 1966 and Etana *et al.*, 1994). The reduction of the bulk density at higher water contents is due to the fact that the amount of water greater than the critical

water content, reduces the compressibility of the soils by filling the pore space. As the water is incompressible (Felt, 1965) an increase in water content will result in a progressive reduction in the ease with which soil particles can be packed.

The maximum bulk densities from different soils were correlated with the percentage of silt plus clay content and organic matter (loss on ignition). The relationship between the maximum bulk density and silt plus clay can be represented by two complemental equations which virtually split the soils into two major groups namely those with less and those with more than 25% silt plus clay or a loss on ignition (LOI) of 3.6%, is the dividing line:

$$\text{Silt + clay} < 25\%: \quad BD_{max} = 1.613679 + 0.034991*(S+C) - 0.00077*(S+C)^2 \qquad (3.4a)$$

$$> 25\%: \quad BD_{max} = 2.146071 - 0.00378*(S+C) - 0.000056*(S+C)^2 \qquad (3.4b)$$

or

$$LOI < 3.6\%: \quad BD_{max} = 1.505024 + 0.329408*(LOI) - 0.0539391*(LOI)^2 \qquad (3.5a)$$

$$> 3.6\%: \quad BD_{max} = 2.169785 - 0.04872*(LOI) - 0.00018*(LOI)^2 \qquad (3.5b)$$

A procedure was developed for determining the minimum bulk density of soils. The minimum bulk density represents a reference value for loose soils or the lower limit of soil compaction. The minimum bulk density (BD_{min}, Mg m^{-3}) can be estimated with equations where the silt plus clay (S+C, %) or loss on ignition (LOI, %) are independent variables:

$$BD_{min} = 1.642 - 0.11121*\ln(S+C) \qquad (3.6)$$

$$BD_{min} = 1.44 - 0.12805*\ln(LOI) \qquad (3.7)$$

Samples from the forestry soils were obtained from Dr. C.W. Smith, Institute for Commercial Forestry, University of Natal, Pietmaritzburg. The minimum bulk densities of the samples were determined using the procedure developed for this study. The

maximum bulk densities and other variables were obtained from Smith (1995). The maximum and minimum bulk density relationships with silt plus clay percentage of the forestry soils were compared with those for the Free State soils. Figures 3.11 and 3.12 show that the relationships between silt plus clay and maximum bulk density and the minimum bulk density respectively using combined data, differ little from the relationships for the soils in the Free State alone. It is therefore possible to estimate the maximum (BD_{max} , Mg m^{-3}) and the minimum (Bd_{min}, Mg m^{-3}) bulk densities of South African soils regardless the type of mineralogy using the following equations:

Silt + clay < 25%: $BD_{max} = 1.6864 + 0.02133*(S+C) - 0.0004*(S+C)^2$ (3.11a)

> 25%: $BD_{max} = 2.1527 - 0.00668*(S+C) - 0.000023*(S+C)^2$ (3.11b)

$BD_{min} = 1.6925 - 0.1245*\ln(S+C)$ (3.12)

The maximum and minimum bulk densities were used to define the concept of a relative bulk density which serves as an indicator for the degree of compactness of a soil. The relative bulk density (RD) was defined as:

$$RD = \frac{BD - BD_{min}}{BD_{max} - BD_{min}} \quad (4.4)$$

Where: BD – measured bulk density of a soil (Mg m^{-3}).

BD_{min} – minimum bulk density of the same soil, measured or estimated with Equation 4.6 (Mg m^{-3})

BD_{max} – maximum bulk density of the soil, measured or estimated with Equation 7.5 (Mg m^{-3}).

Resistance offered by soils to root penetration, as indicated by the penetrometer resistance at the critical water content, was used to obtain the bulk densities of the soils at conditions which could be defined as very loose, loose, moderately dense, densely and very densely compacted. The mean relative bulk densities for all the soils were calculated

for each of these classes and threshold values were obtained. These threshold relative bulk densities can be used to determine the degree of compactness of soils.

Degree of compactness	Relative bulk density
Very loose	< 0.3
Loose	0.3-0.4
Moderate	0.4-0.5
Dense	0.5-0.6
Very dense	> 0.6

Compaction may occur in soils of different texture but certain soil texture classes are more susceptible to excessive compaction than others (Bodman & Constantin, 1965). This means that the packing behaviour of soils under external loads is also influenced by the degree of grading which is a function of the silt plus clay content. The degree of grading influences the compressibility of soils which is the amount of increase in bulk density with increasing uniaxial loads at a specific water content. The compression index is the slope of the linear compression curve relating bulk density to the $\log_{10}$ of the uniaxial load. Panayiotopoulos & Mullins (1985) stated that sandy and coarse silty soils are often considered among the most suitable for crop production due to their high infiltration rate and because they can be cultivated and traversed soon after heavy rainfall. These soil types are extensively cultivated in South Africa (Bennie & Van Antwerpen, 1988). The high resistances against most penetration of these apedal soils can present a management problem. According to Smith (1995) this is due to the rigidity of the sandy soils making them resistant against deformation resulting in low compressibility.

Compression curves were determined for all the soils at a single water content, the critical water content at which the maximum bulk density was obtained. From these curves the compression indices and the intercepts were determined. The compression indices correlated well with the clay, silt plus clay and organic matter (loss on ignition) contents. Curvilinear equations were derived for the prediction of the compression index

of a soil from the easily measured soil properties, clay, silt plus clay or organic matter contents.

The compression index of a soil indicates the ease with which the soil can be compressed. The sandy soils had the lowest compression indices, indicating a high resistance to compression. The compression index increased with an increase in clay or silt plus clay contents and loss on ignition.

The intercepts of the curves decreased linearly with increasing silt plus clay contents. To illustrate the value of compression index as an indicator of the deformability of soils, root growth can be used as an example. Bennie & Botha (1986) stated that in apedal sandy soils roots do not have the chance of growing through cracks as happens in structured soils. They elongate by exerting pressure and displacing soil particles. The rate of root elongation depends on the deformability of the soil which is well related to the compressibility of the same soil. Soils with high compressibility are more susceptible to excessive compaction under loads but in the uncompacted state it is more suitable for root growth because the energy required to deform them is lower. Soils with silt plus clay contents between 25 and 35% are the most suitable for root growth as they can be deformed easily, provided that they are in an uncompacted state allowing the roots to expand either axially or longitudinally.

The relationship between compression index and silt plus clay content obtained in this study was compared with the one reported by Smith (1995), and very good agreement was found. By combining the data it was possible to derive an equation for the prediction of the compression index (CI) for South African soils using the silt plus clay content (S+C, %).

$$CI = 0.10 + 0.01283*(S+C) - 0.0000833*(S+C)^2 \qquad (5.5)$$

CI-values estimated with this equation are only valid for bulk density calculations (Equation 5.6) obtained at uniaxial loads varying between 200 and 1800 kPa at the critical water contents (Equation 3.13).

The compactibility of soils, either defined in the classical way (where it is equal to maximum bulk density) or as the difference between the maximum and minimum bulk densities, increases with the replacement of large sand particles by finer silt plus clay until a critical silt plus clay content of 25% is reached. For soils with silt plus clay contents higher than 25% the compactibility decreased. The difference in slopes of the curve before and after the point of inflection may be attributed to additional sand properties which have not been investigated, namely skewness of the size distribution and shape of particles (Figure 6.2). The proposed procedure for calculating compactibility takes into account the range within which the bulk density of the soils can vary by using the minimum bulk density as the lower and the maximum bulk density as the upper limit of compactibility. The maximum and minimum bulk densities for a range of silt plus clay contents were calculated using Equations 7.5 and 7.6, respectively. The compactibility, which is the difference between the two values, was correlated with the silt plus clay contents to derive Equation 7.9 with which the compactibility (Comp, Mg m^{-3}) of soils, agricultural and forestry, in South Africa can be calculated.

Silt + clay < 25%: $\quad Comp = 0.1607 + 0.033472*(S+C) - 0.00053*(S+C)^2$

> 25%: $\quad Comp = 0.7481 - 0.0024*(S+C) - 0.00003*(S+C)^2$

(From Figure 6.2)

Combining compactibility and compressibility can produce a more reliable prediction of the susceptibility of soils to excessive compaction. Five classes were proposed for the classification of soils with < 35% silt plus clay according to their susceptibility to compaction. Sandy clay loam soils seem to be the most susceptible to compaction as they require relatively low uniaxial loads to change their bulk densities from minimum to maximum. These soils are suitable for engineering activities where soils are required that need less energy to compact to high densities and strengths (McKyes, 1985). Similarly,

these soils in an uncompacted state are more suitable for root growth as they deform easily when the roots grow. In contrast, the deformability of these soils is problematic for traffic. Under wet conditions they cannot resist deformation when submitted to external pressure, compared to sandy soils which exhibit better trafficability when wet.

One of the aims of soil management for crop production is to avoid excessive soil compaction. Soil compaction has many consequences. Among them it decreases root growth and yields, needs higher energy inputs for soil tillage (Gill, 1971) resulting in higher costs which can become unaffordable (Bennie & Krynauw, 1985; Boone, 1986 and Raghavan *et al.*, 1990) and it may persist for many years (Soane *et al.*, 1982 and Voorhees, 1992). Subsoiling is recommended to break the compacted layers. Hartge & Sommer (1980), Fortune & Burke (1987) and Voorhees (1992) have mentioned that a subsoiled field can be easily recompacted by traffic and similar external forces. It seems that the avoidance or control of soil compaction is a better solution than corrective measures.

For the design of a soil management plan, a knowledge of the soil properties influencing the compactibility and compressibility are very important. The magnitude of density changes under load depends on soil texture, soil water content, contact pressure and the number of passes (Raghavan *et al.*, 1990; Gameda *et al.*, 1987b and Blunden *et al.*, 1992). Boone (1986) stated that during agricultural activities with random traffic only a small part of the field remains untouched by wheels whereas the greater part is affected more than once, even up to eight times. A management plan which avoids as much as possible traffic on the field, or whereby the traffic is controlled and restricted to fixed lanes is well recommended.

Based on reports from many authors using soils with a large range of textures, it can be concluded that the contact pressure between tractor tyres and the soil generally vary between 80 and 360 Kpa (Mullins & Panayitopoulos, 1984; Burt *et al.*, 1990; Block *et al.*, 1994; Morgan et al., 1993; Hadas, 1994 and Vermeulen & Klooster,1992). Similarly, Scholefield et al. (1985) found that the maximum pressure applied vertically by a walking

cow of 530 Kg was 300 Kpa. Interpolating the pressure values by tractor wheels and hoofs of cows in the Figure 6.3, for soils at the critical water content, it can be concluded that soils with more than 15 % silt plus clay content are susceptible to be compacted under loads similar to those exerted by tractors and livestock to critical densities (Table 7.1).

Table 7.1 Critical contact pressures as uniaxial loads for soils with different silt plus clay contents

S+C	UL	Comp	BD_{max}	BD_{min}	CI	Intercept	CD
5	1961	0.291	1.783	1.492	0.072	1.4294	1.667
7	916	0.366	1.816	1.450	0.096	1.3862	1.670
7.5	815	0.382	1.824	1.442	0.102	1.3754	1.671
8	737	0.398	1.831	1.434	0.107	1.3646	1.672
9	628	0.427	1.846	1.419	0.119	1.3430	1.675
10	556	0.454	1.860	1.406	0.130	1.3214	1.678
12	469	0.502	1.885	1.383	0.152	1.2782	1.684
13.5	430	0.533	1.901	1.368	0.168	1.2458	1.688
15	403	0.561	1.916	1.355	0.184	1.2134	1.692
20	353	0.633	1.953	1.320	0.233	1.1054	1.700
25	331	0.680	1.971	1.292	0.279	0.9974	1.699
30	269	0.663	1.932	1.269	0.320	0.8894	1.667
33	251	0.650	1.907	1.257	0.343	0.8246	1.647
35	245	0.641	1.891	1.250	0.357	0.7814	1.634
40	241	0.615	1.849	1.233	0.390	0.6734	1.603
45	252	0.587	1.806	1.219	0.419	0.5654	1.571
50	275	0.556	1.761	1.205	0.443	0.4574	1.539
60	371	0.486	1.669	1.183	0.480	0.2414	1.475
70	585	0.409	1.572	1.164	0.500	0.0254	1.409

Legend: S + C – silt plus clay content (%)

UL – uniaxial load (Kpa), calculated with Equation 6.2.

Comp – compactibility (Mg m^{-3})

BD_{max} – maximum bulk density (Mg m^{-3}), calculated with Equations 3.11a and 3.11b

BD_{min} – minimum bulk density (Mg m^{-3}), calculated with Equation 3.12

CI – Compression index, calculated with Equation 5.5

CD – critical density (Mg m^{-3}), calculated with Equation 6.1

Chamen *et al.*, (1992) and Van den Akker, Arts, Koolen & Stuiver (1994) found that reducing the tyre pressures, offered a potentially cheap and simple means of reducing soil damage on sandy soils though it might cause considerable damage to the tyres. Based on the findings of this study it is recommended that under wet conditions for which the critical water content is considered to apply, the contact pressures (uniaxial load) shown in the Table 7.1, should be considered as the maximum values allowed for the field operations.

The proposed classes and threshold values for the relative bulk density of soils can be used to determine the degree of looseness or compaction for better planning and for monitoring soil conditions under recommended soil management practices.

Future research opportunities

This research dealt with the prediction of compactibility and susceptibility to compaction based on texture and organic matter. The factors considered were shown to be reliable elements for such predictions. To create more possibilities for prediction of the same parameters, it is suggested that the following aspects need further research:

1. The effect of skewness of the size distribution and roundness of sand particles on the comnpactibility and compressibility of agricultural and forestry soils in South Africa.

2. The critical density for specific crops in a large range of silt plus clay soils.

3. The relationship between the intercept of the Virgin Compression Line and the minimum bulk density.

4. An economic analysis to evaluate the loss due to soil compaction.

5. The optimum tyre inflating pressure for each type of soil.

ABSTRACT

Crop production in the Free State is mainly performed on sandy soils. The compaction of these apedal soils can present a management problem which affects crop yields and financial returns. In addition, environmental problems such as soil erosion and siltation of rivers may result.

The main objective of the study was to see whether the easily measured soil properties, texture and organic matter, could be used to classify the compaction degree of soils and to predict their compaction susceptibility. Additional objectives were to define critical densities beyond which crop growth would be impeded, to test the applicability of the relative bulk density concept proposed by Bennie & Van Antwerpen (1988) and to propose a procedure for the prediction and classification of the compactibility of the soils in the Free State. Finally, the results were compared to the data from forestry soils (Smith, 1995) for more humid conditions.

Twenty two (22) samples of selected soils covering a large range of soil texture variation were submitted to a determination of the maximum bulk density (using the Proctor test), minimum bulk density, uniaxial compression test and penetrometer resistance measurements. A procedure for the determination of minimum bulk density was developed.

Good quadratic relationships were obtained between the maximum bulk density and silt plus clay or organic matter content as loss on ignition. The minimum bulk density can be predicted from the silt plus clay percentage or loss on ignition. When the actual bulk density and the silt plus clay or loss on ignition percentages are available, the relationships allow the estimation of maximum and minimum bulk densities. The measured bulk density can then be used to calculate the relative bulk density of a soil. Threshold relative bulk density classes (5) were derived which can be used to evaluate the degree of denseness or looseness of the soil, and its suitability for different applications.

It is proposed that compactibility be regarded as the difference between the maximum and minimum bulk densities, instead of simply the maximum bulk density. Different classes of compactibility were derived. The compression index of all the soils at the critical water content showed good relationships with the silt plus clay, clay or organic matter contents of the soils. Compressibility classes were also established. A combination of the compactibility and compressibility of soils was used to determine its susceptibility to compaction. Compaction susceptibility was classified into five groups varying from very low to very high degrees of susceptibility for apedal soils.

The data set from this study when combined with the data reported from the study of forestry soils by Smith (1995), made it possible to derive equations with a more universal applicability for the prediction of the maximum and minimum bulk densities, critical water content as well as compression index.

The results from this investigation, when properly transferred in popular terminology set guidelines for the evaluation of the degree of compactness and compaction susceptibility of soils. These guidelines will allow persons responsible for soil evaluation to draw more meaningful conclusions from bulk density measurements.

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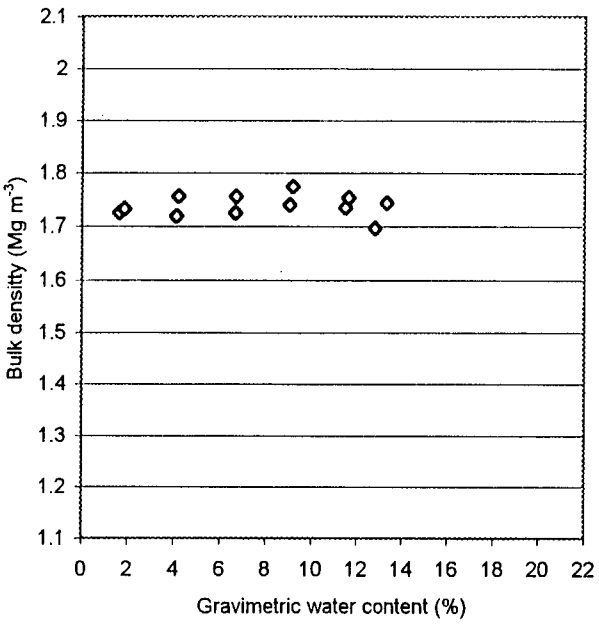
Appendix 3.1: The relationship between the bulk density and gravimetric water content for the soils obtained by the Proctor test. The maximum bulk density values occur at the point of inflection.

(H5A)



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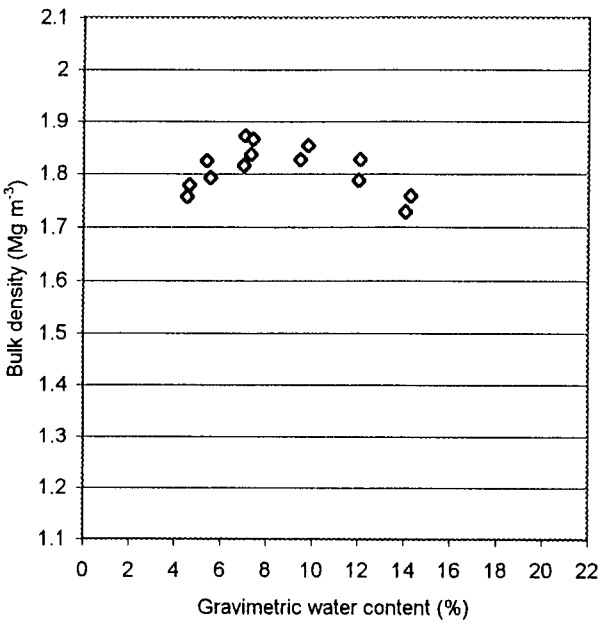

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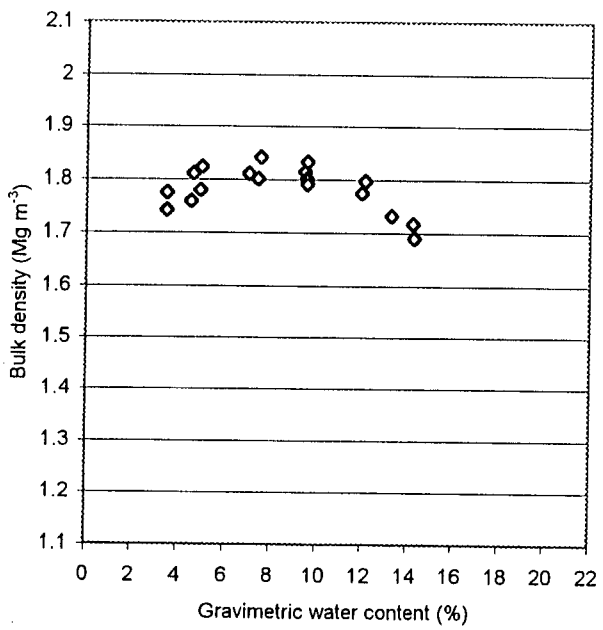

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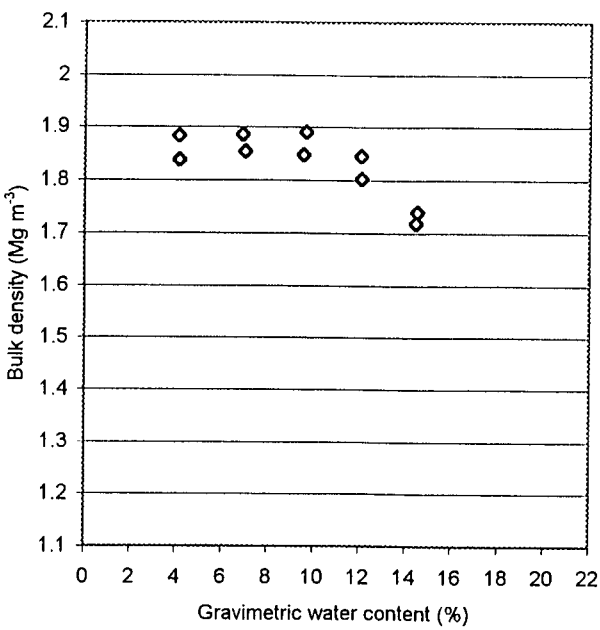
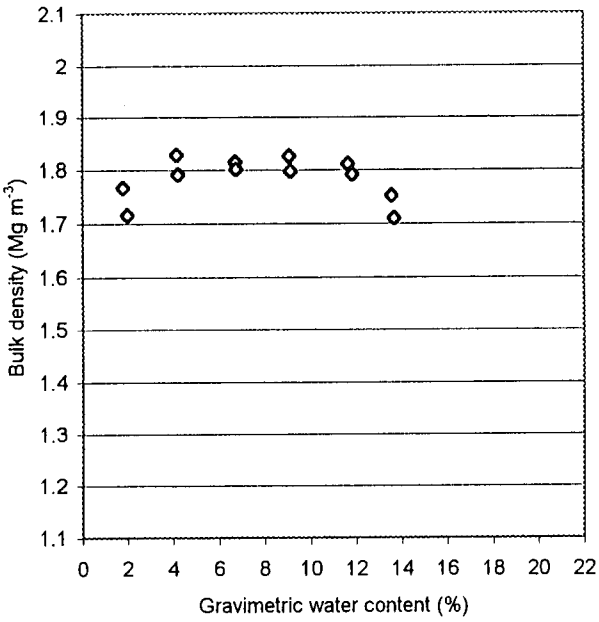


Appendix 3.1: Continued

(H4A)



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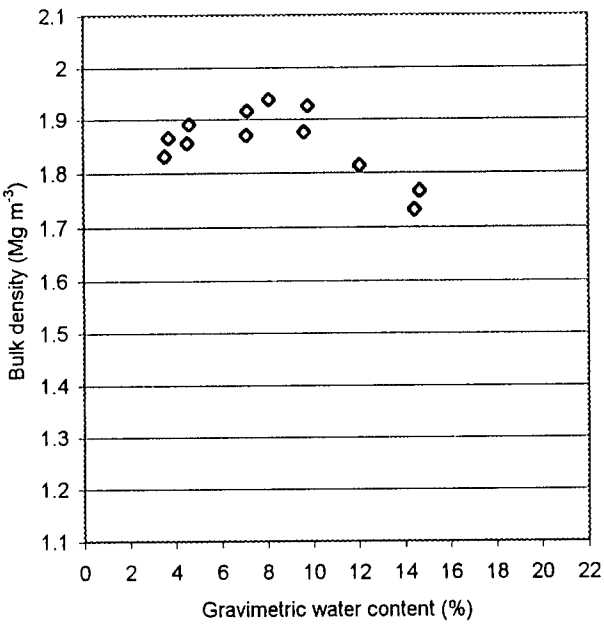

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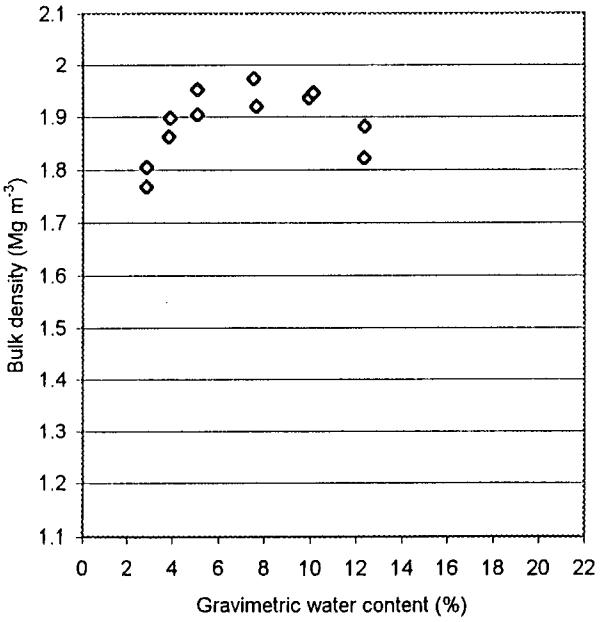
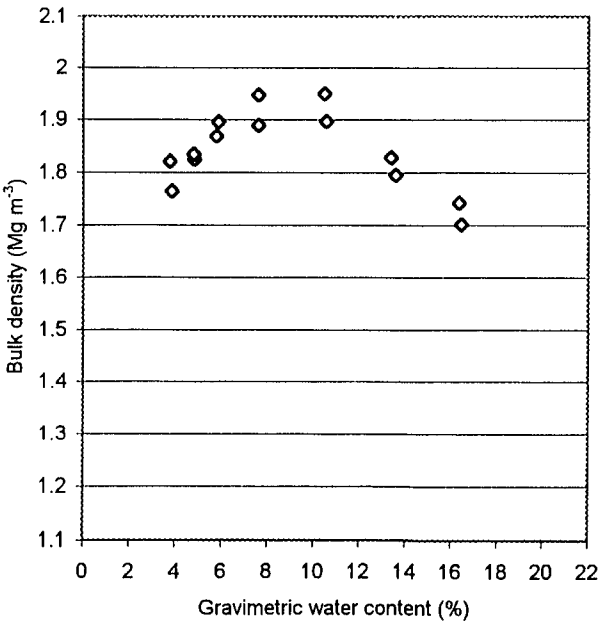
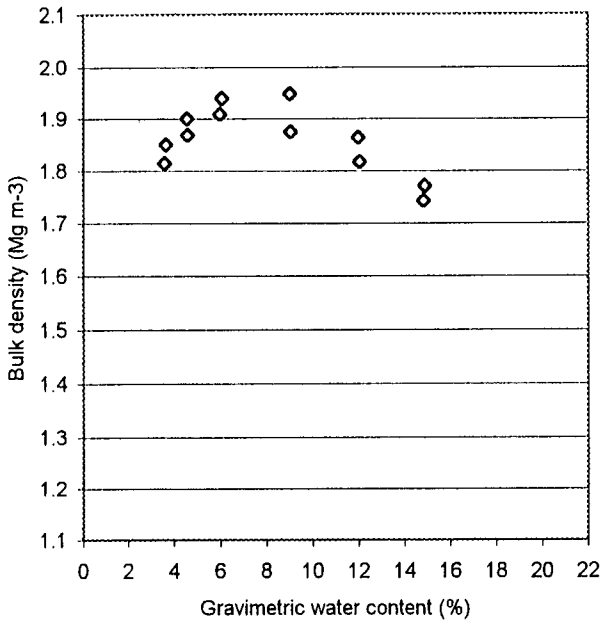


(L3A)

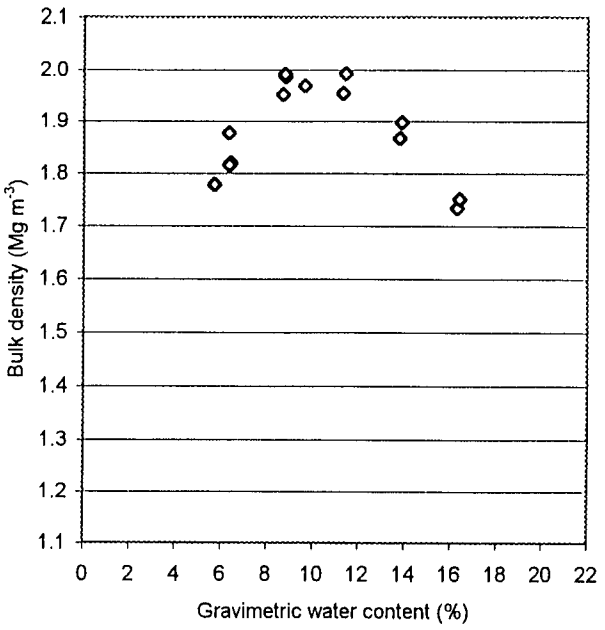


Appendix 3.1 Continued

(L2A)



(B1B)



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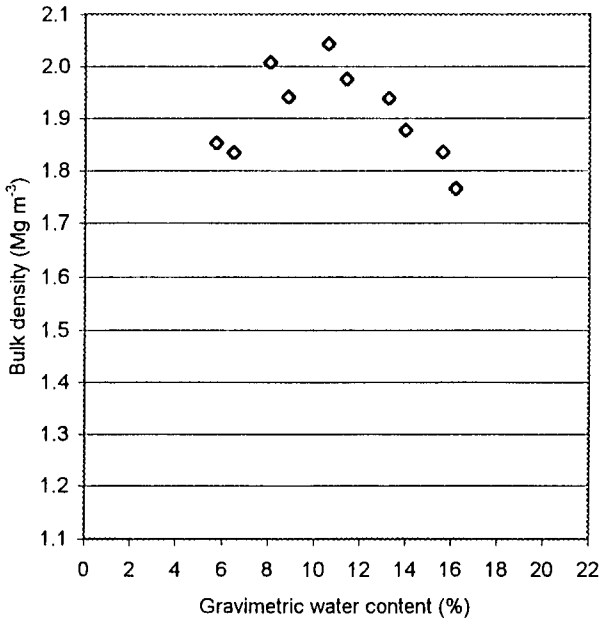

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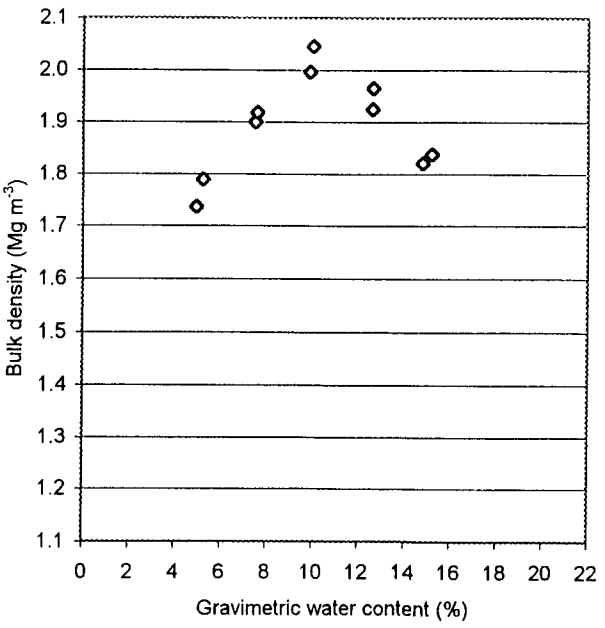
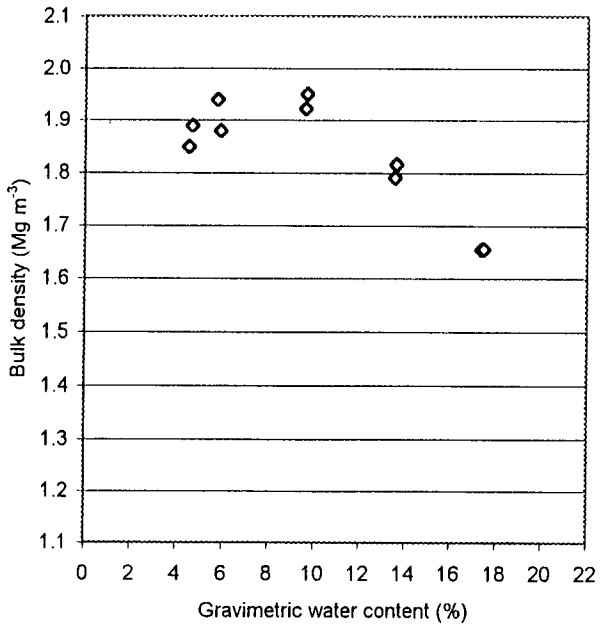


Appendix 3.1: Continued

(L1A)



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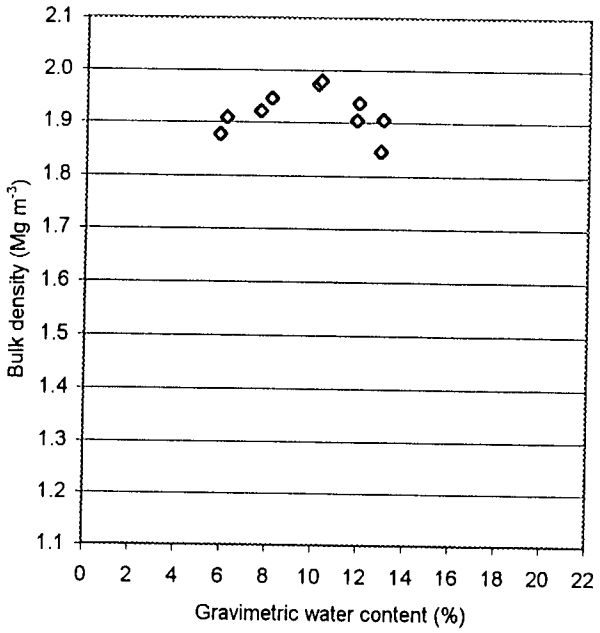

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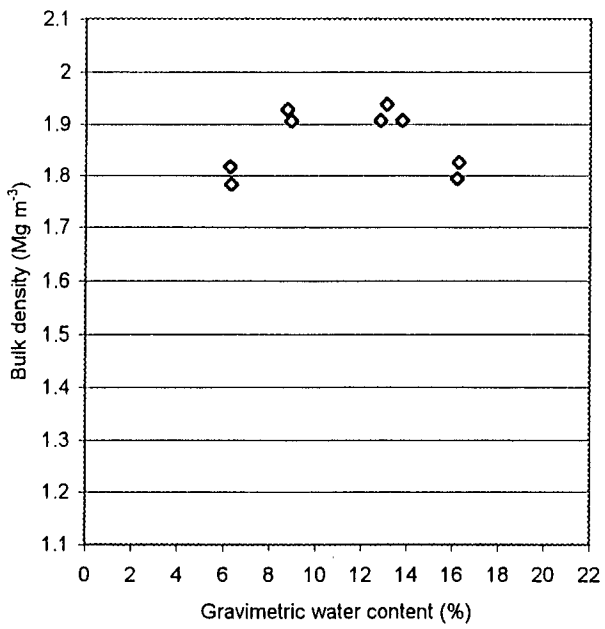

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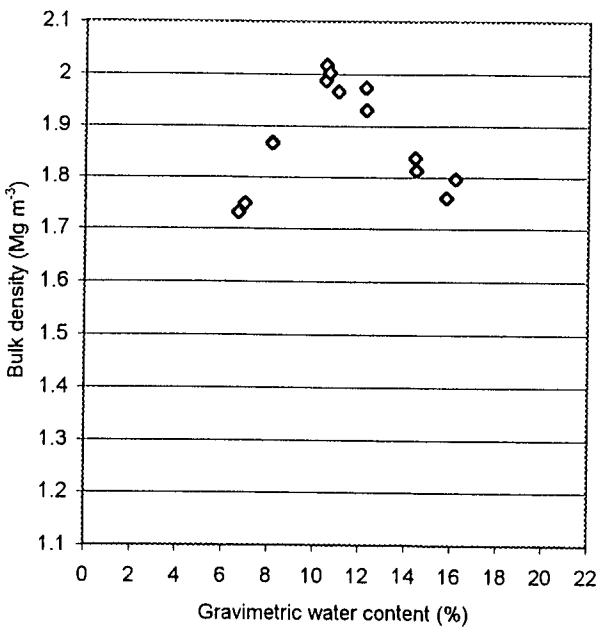
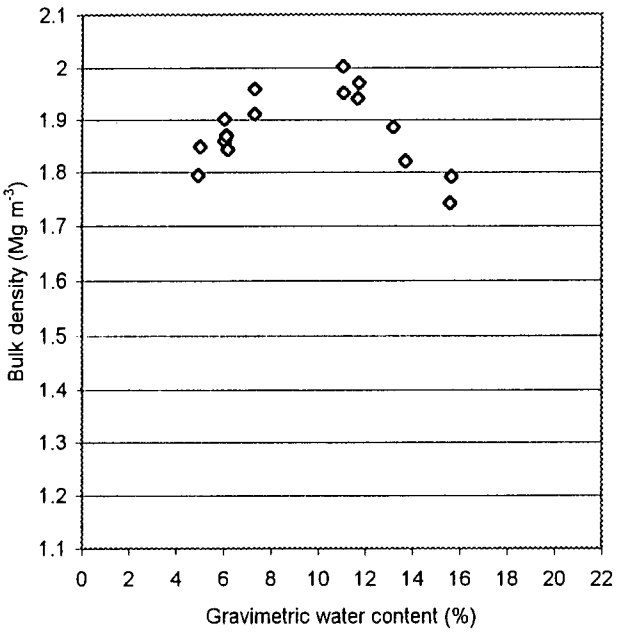


Appendix 3.1: Continued

(L1B)



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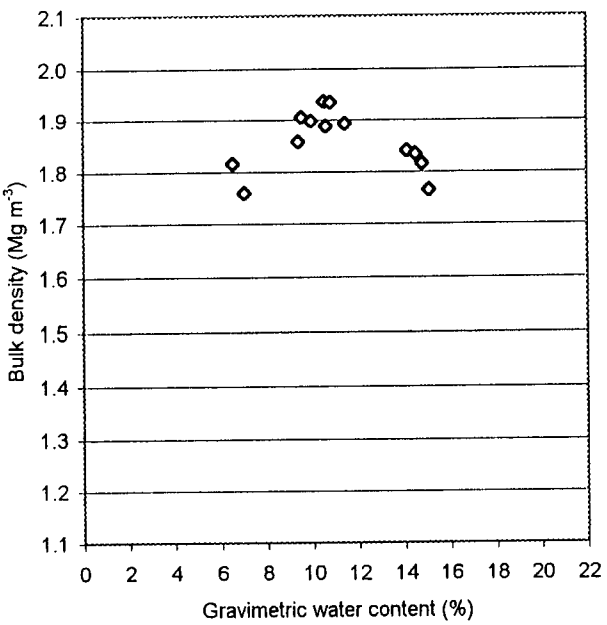

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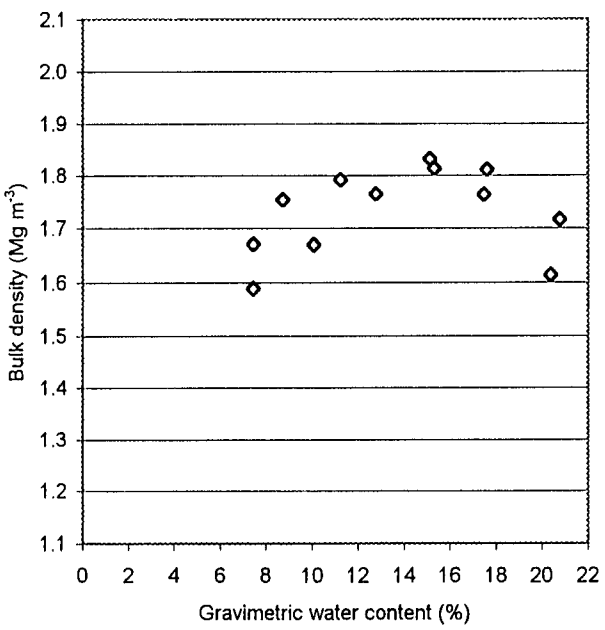

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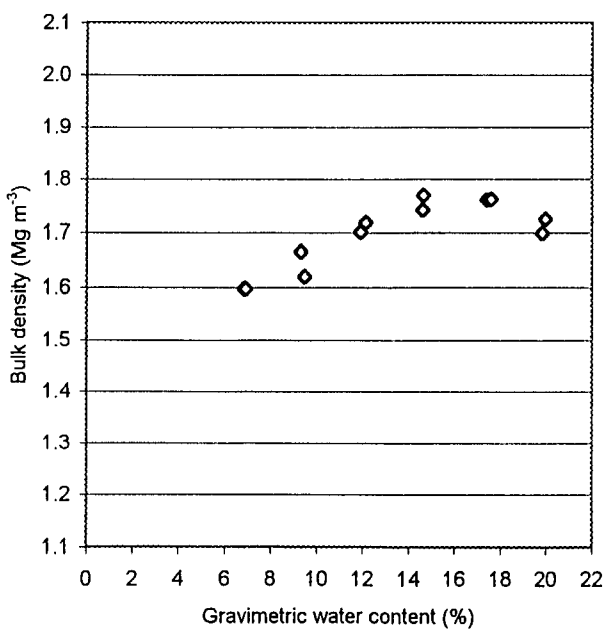

Appendix 3.1: Continued

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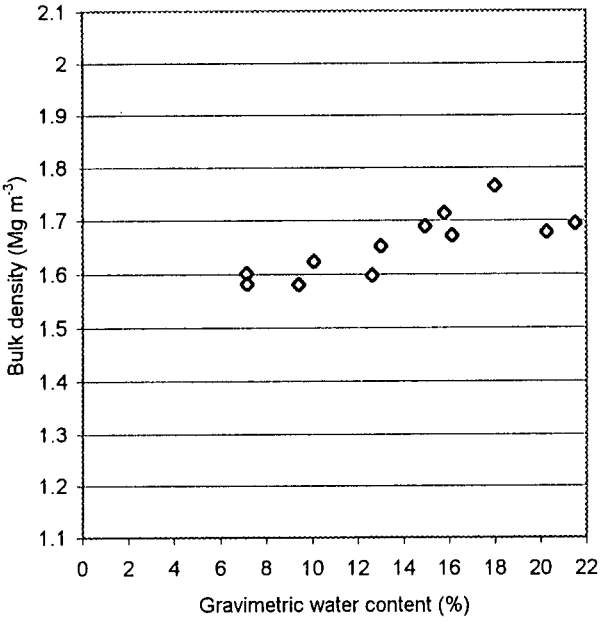

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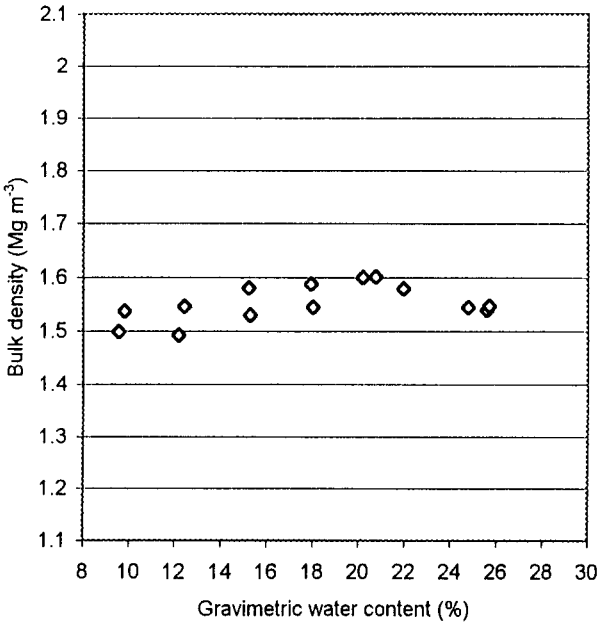
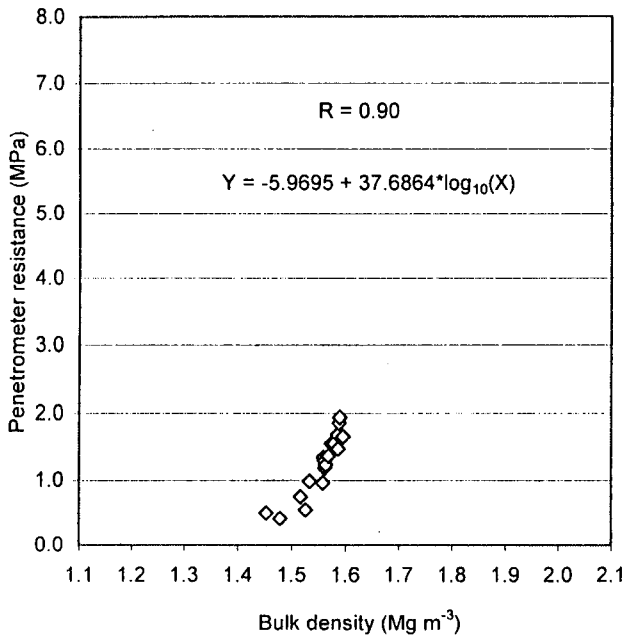


Appendix 4.1: Penetrometer resistance as function of bulk density at the critical water content

(H5A)



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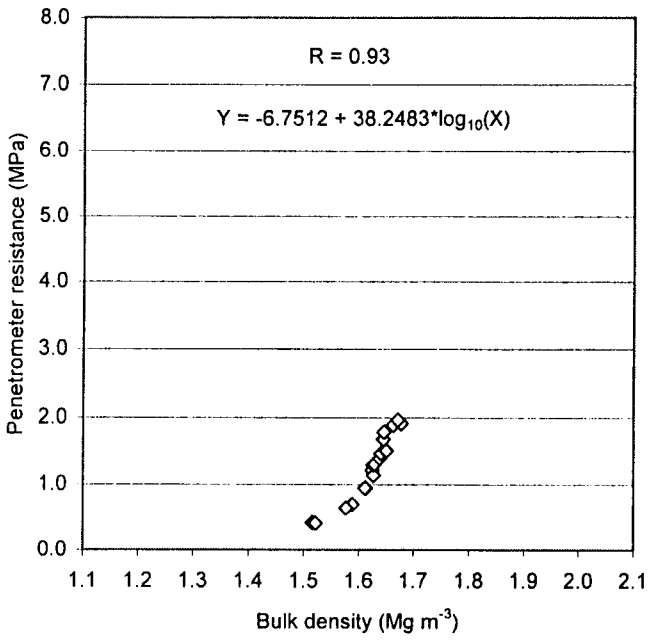
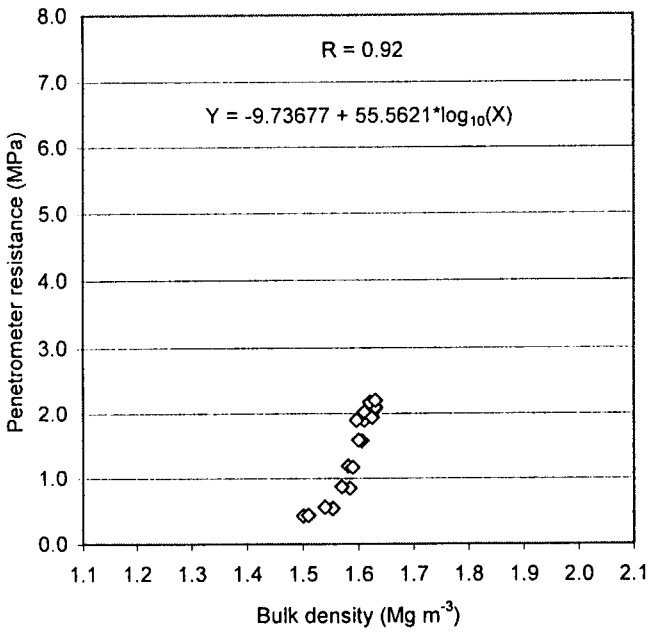


(B1A)



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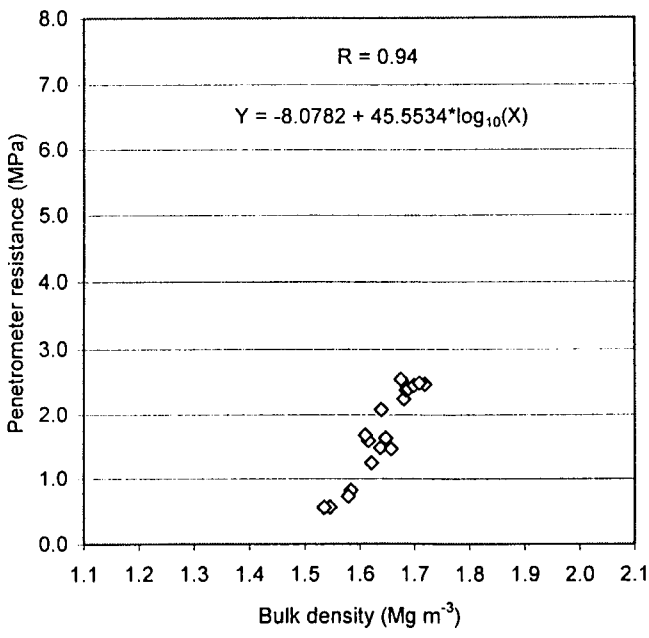
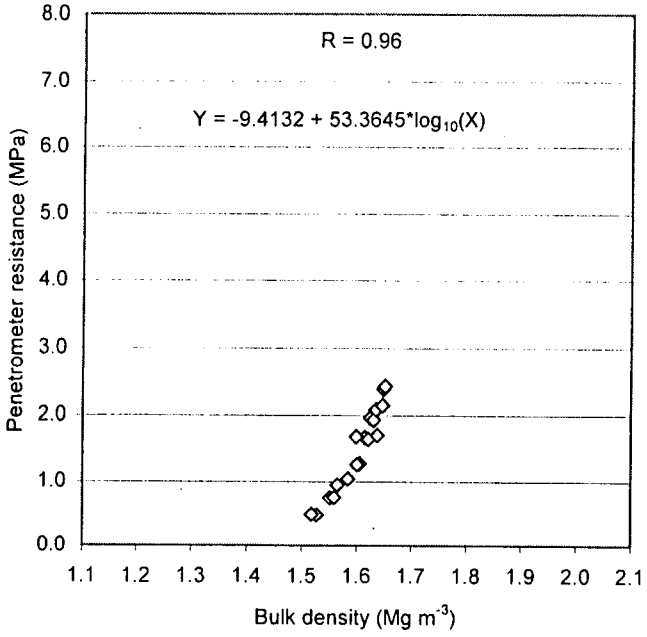


Appendix 4.1: Continued

(H4A)



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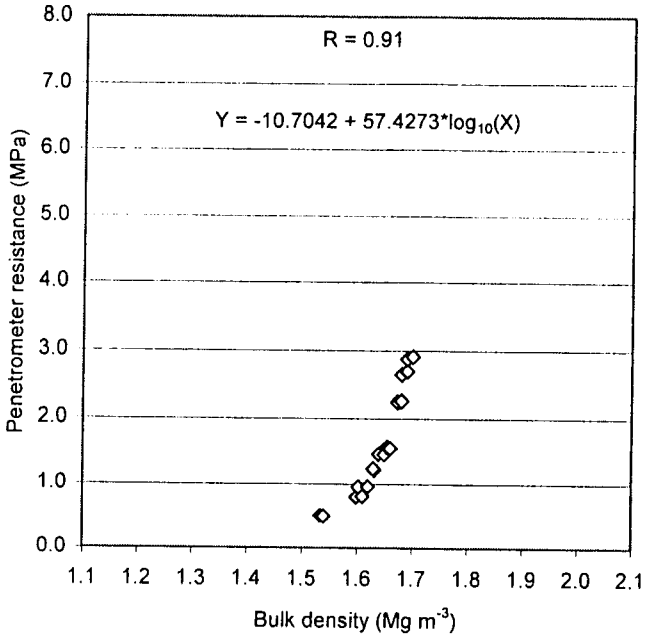

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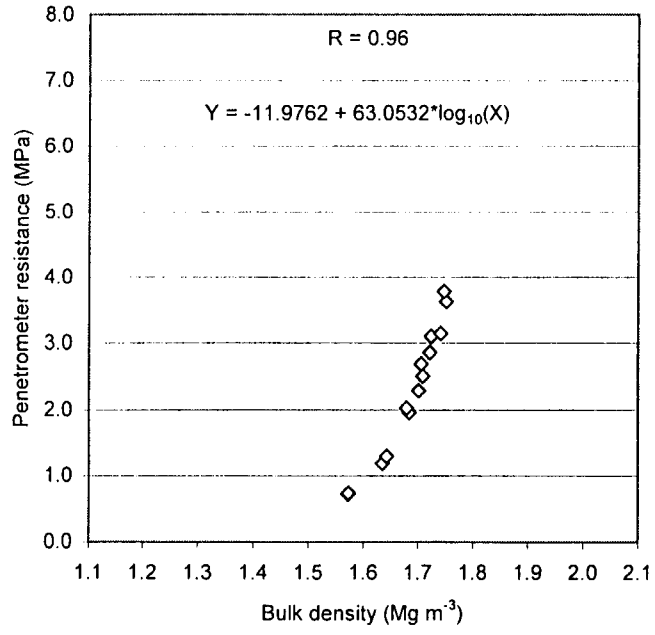

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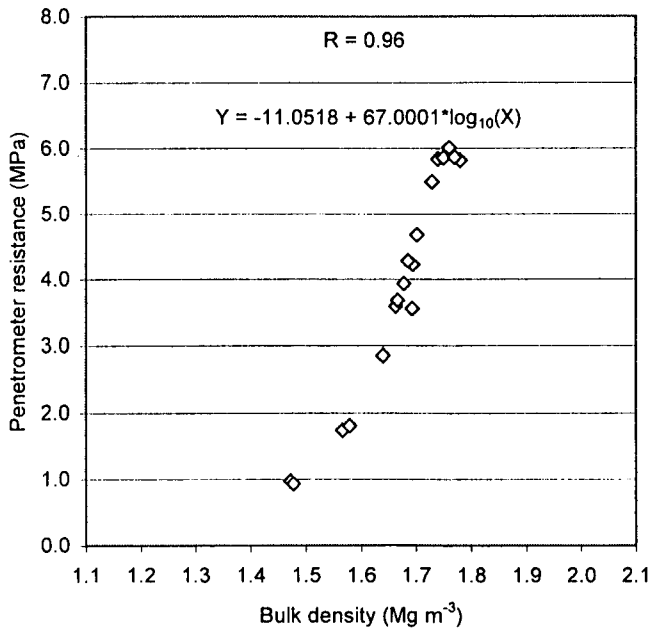
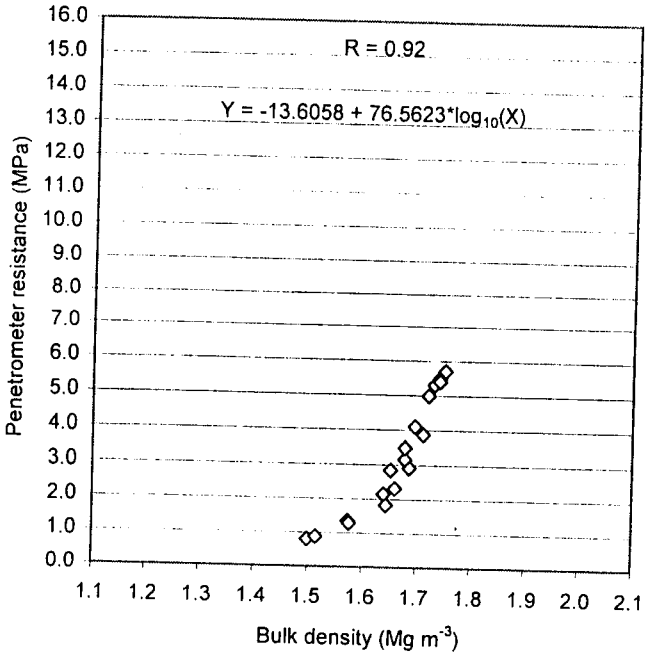
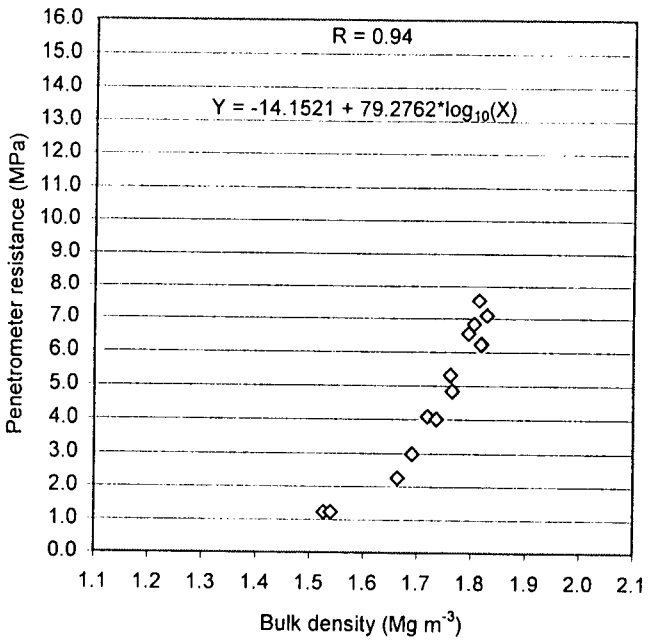


Appendix 4.1 Continued

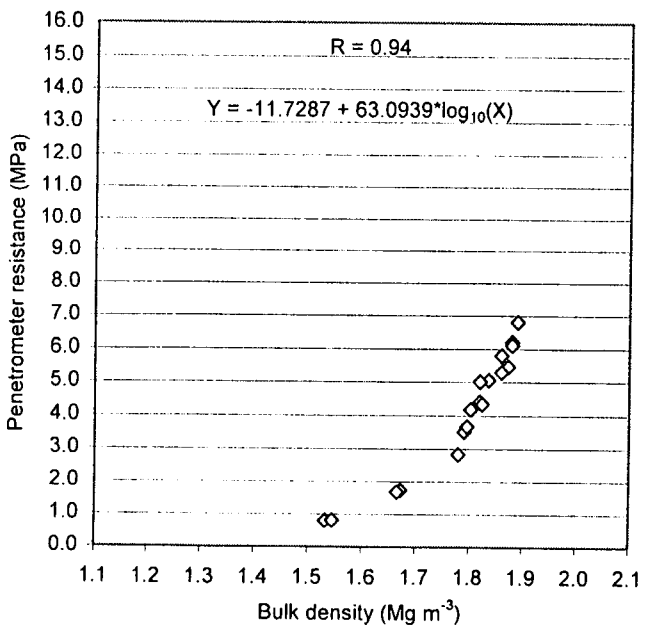
(L2A)



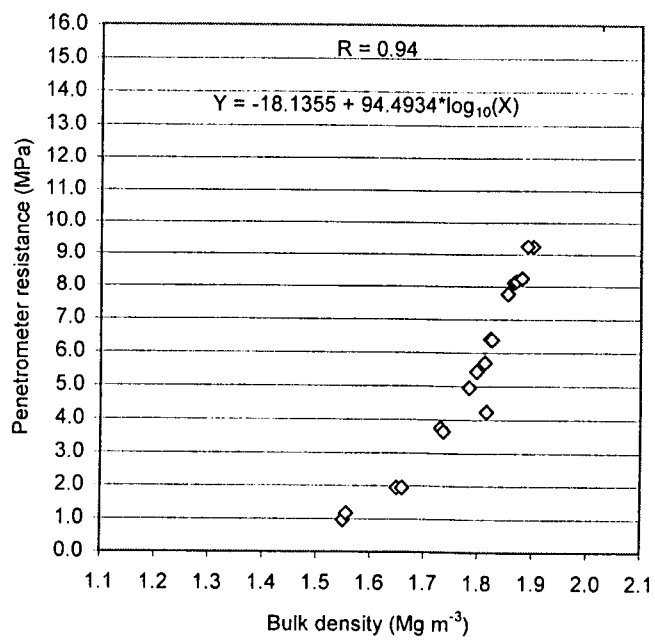
(B1B)



(H1B)

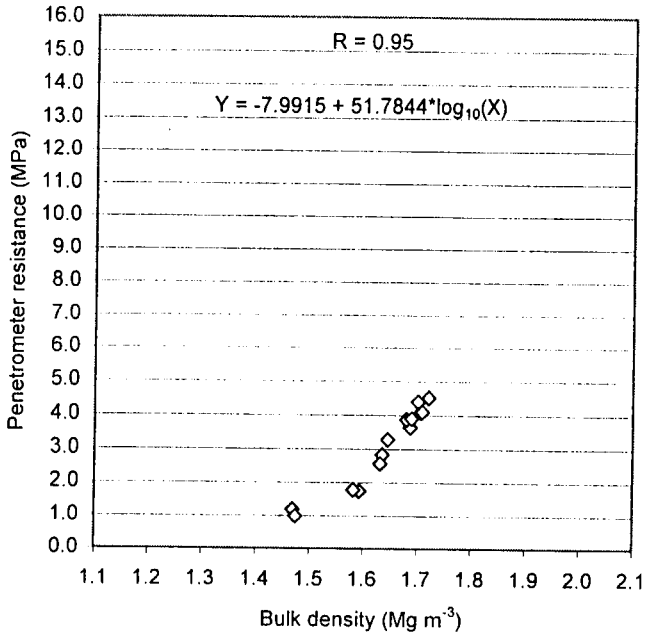


(D2B)

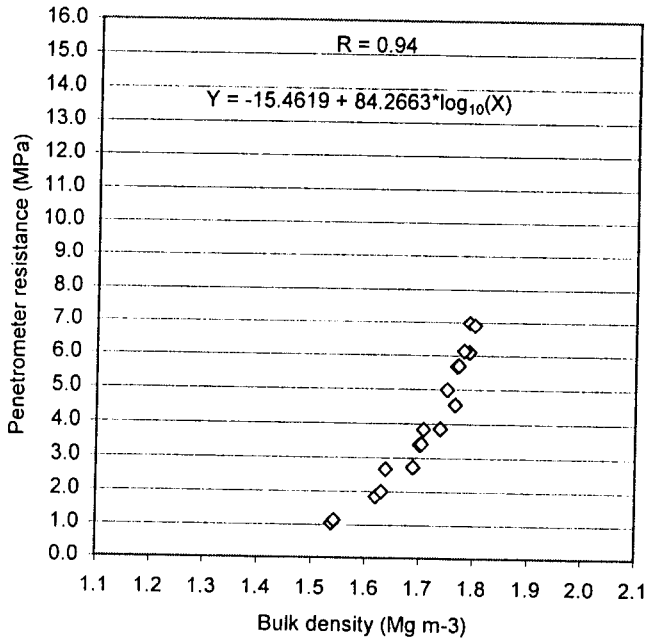


Appendix 4.1: Continued

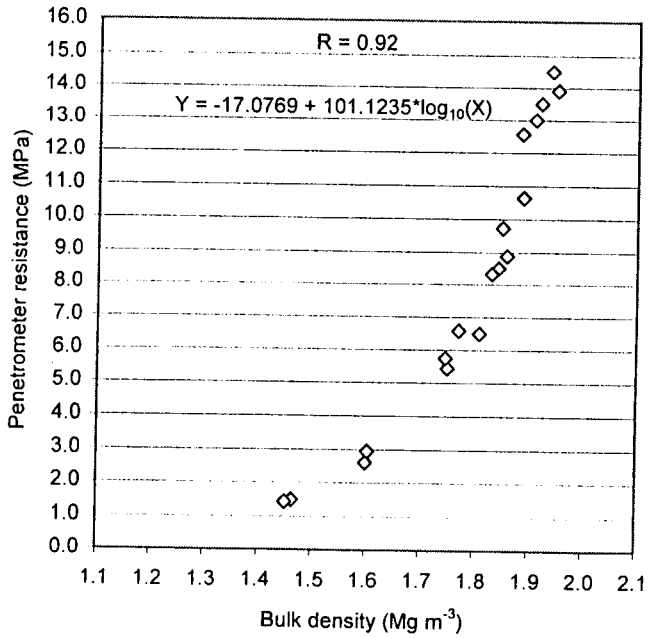
(L1A)



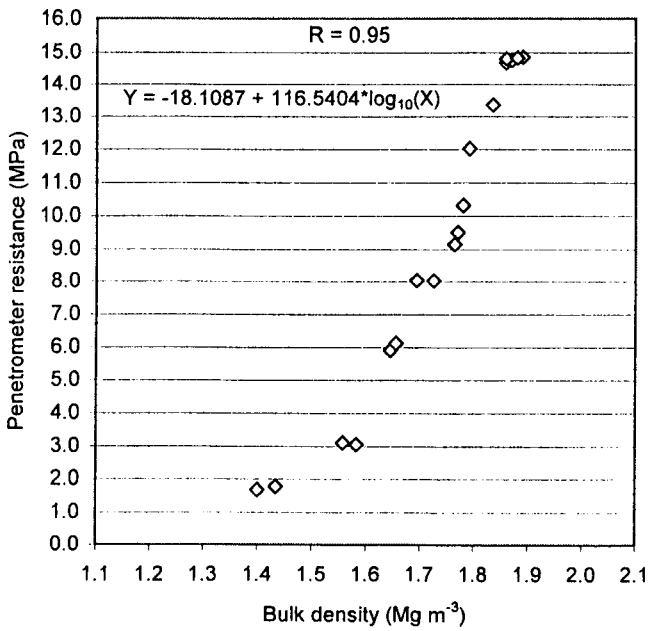
(T2A)



(B3A)

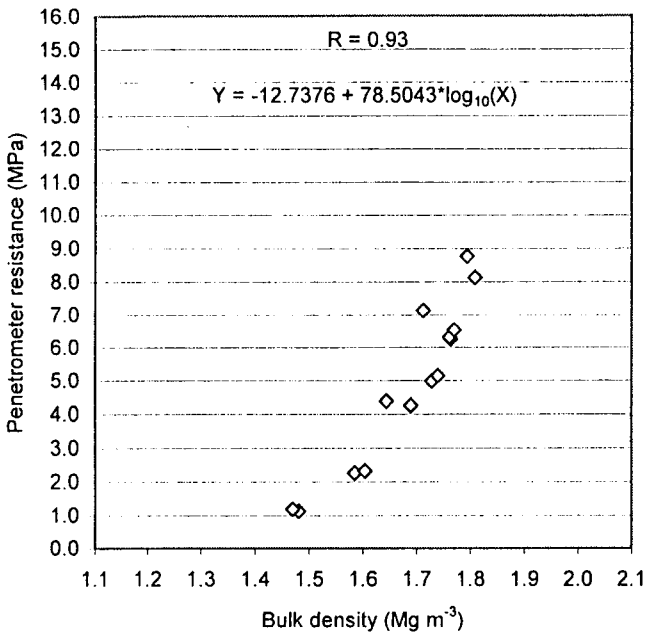


(L3B)

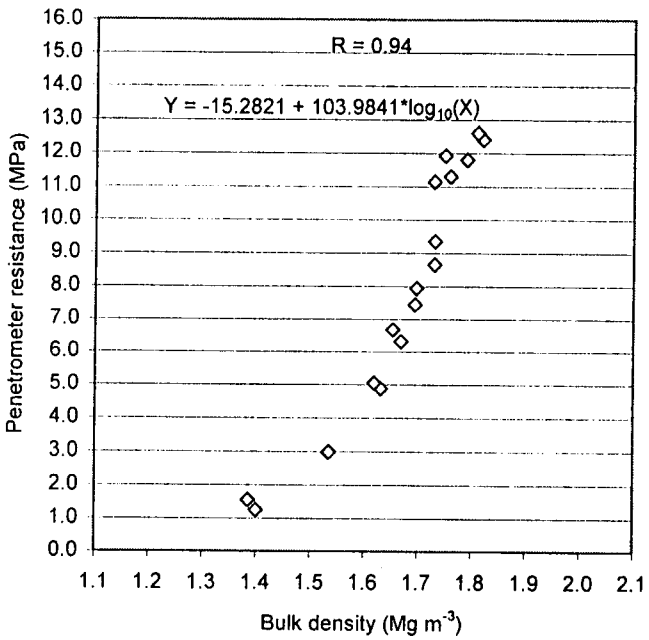


Appendix 4.1: Continued

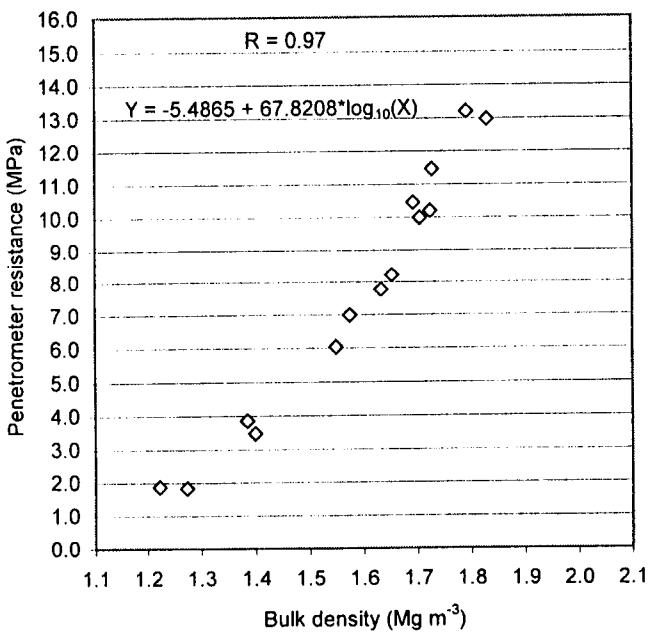
(L1B)



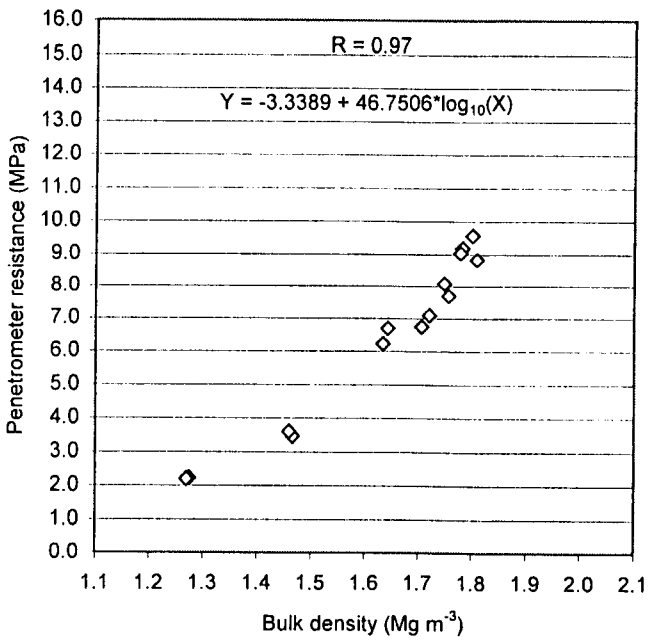
(T1A)



(D3A)

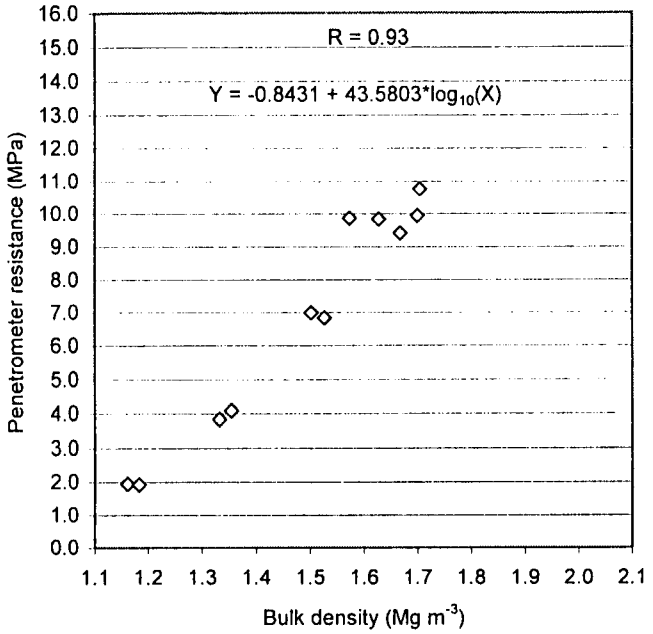


(D1B)

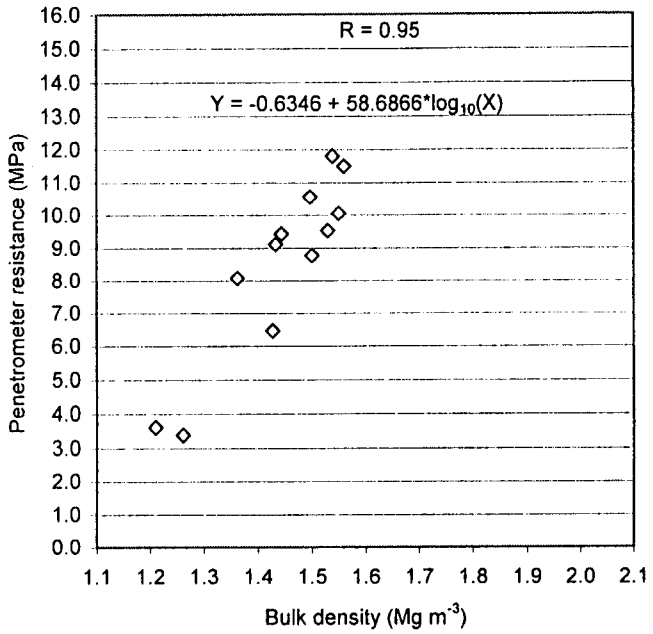


Appendix 4.1: Continued

(D1A)

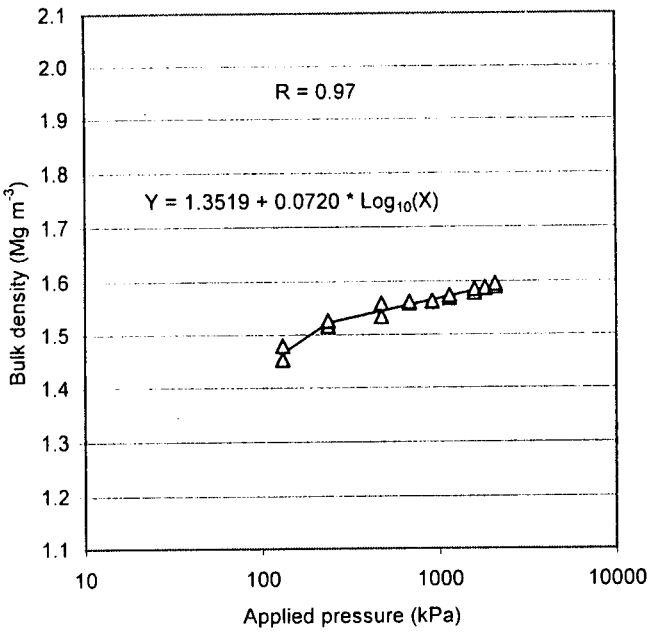


(G1A)

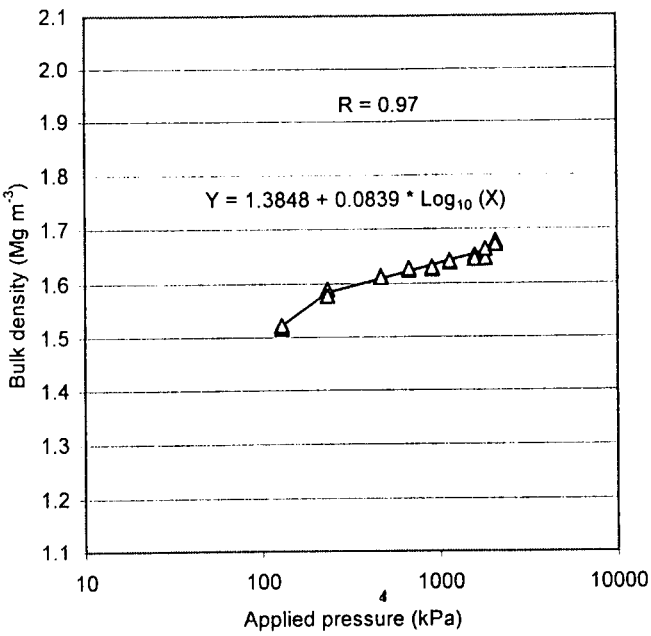


Appendix 5.1: Compression curves of the soils used for the study at the critical water content.

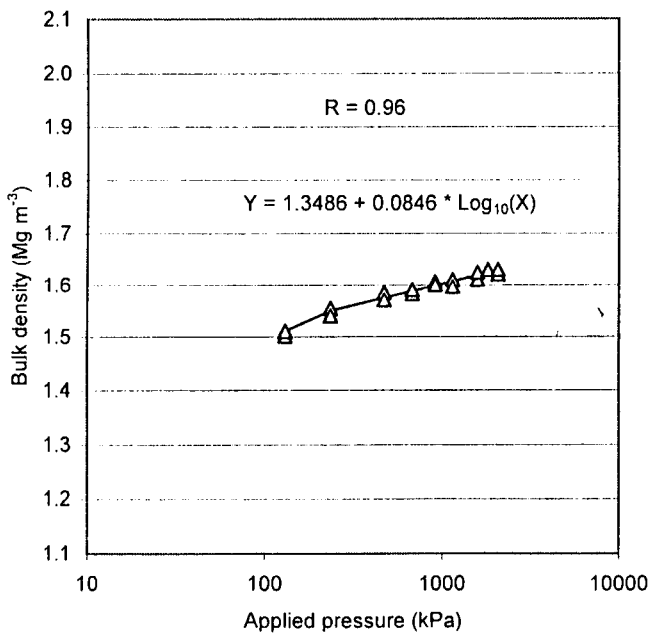
(H5A)



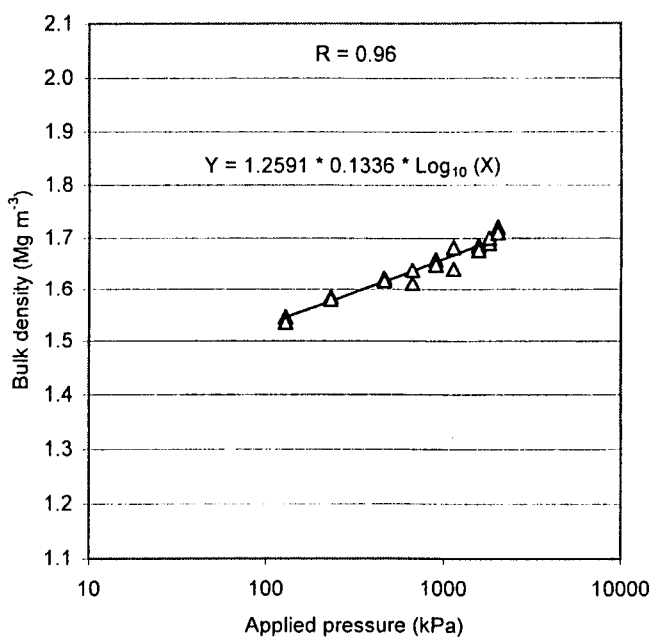
(H2A)



(B1A)

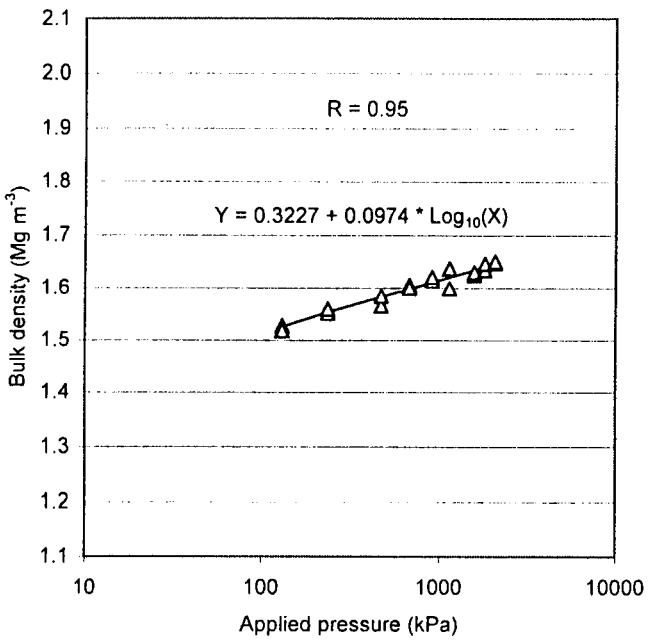


(B2A)

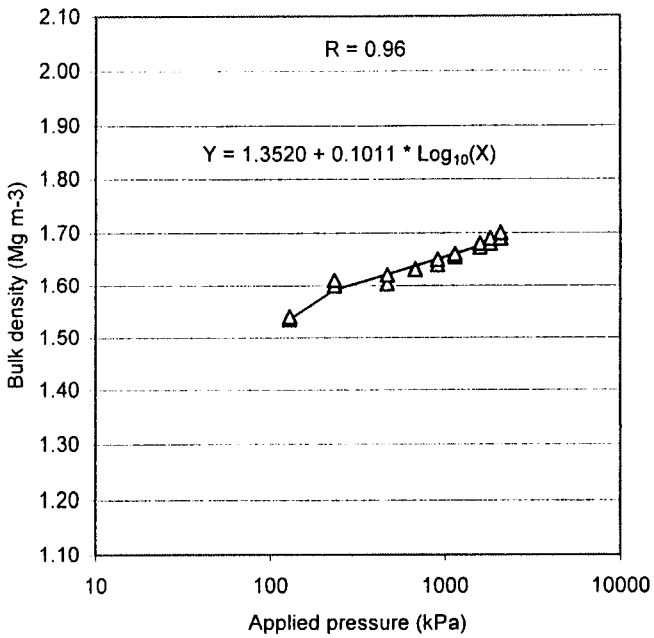


Appendix 5.1: Continued

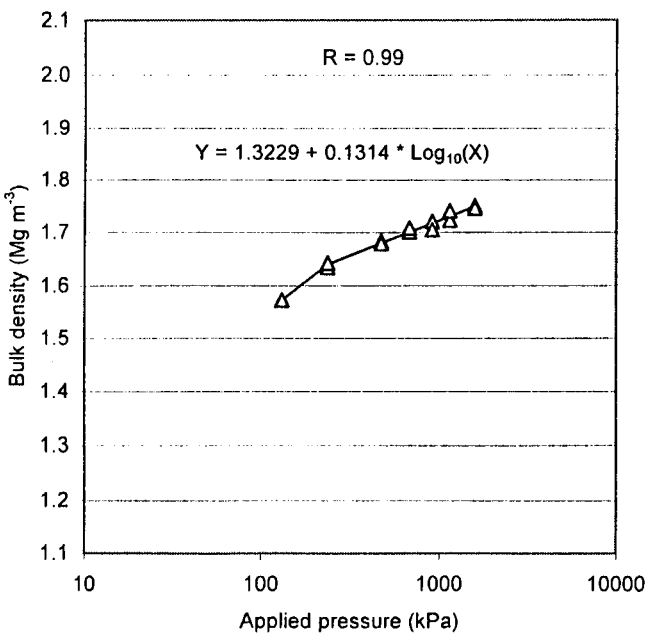
(H4A)



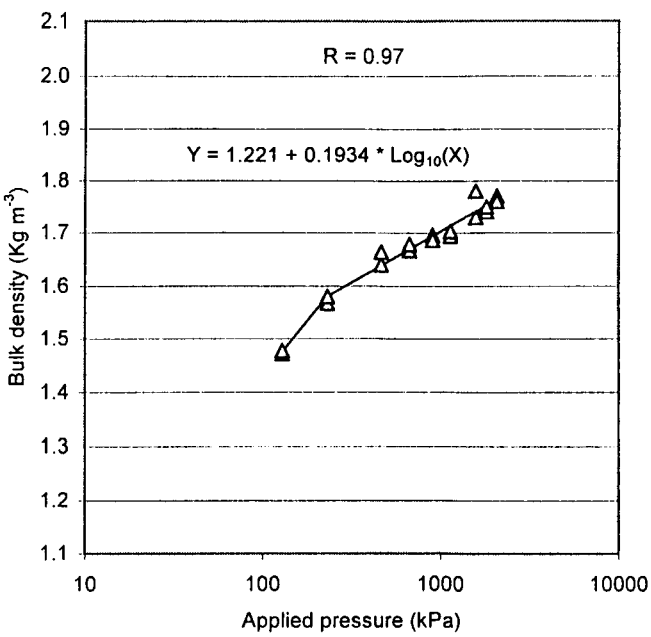
(H3A)



(H1A)

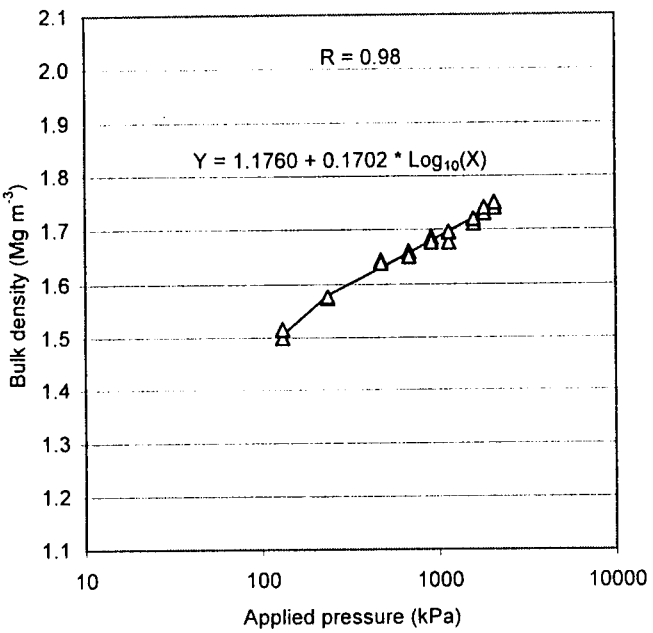


(L3A)

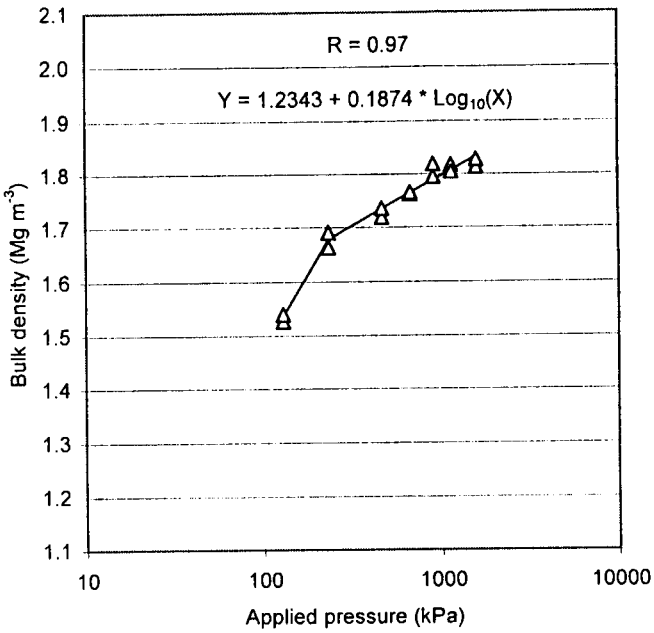


Appendix 5.1 Continued

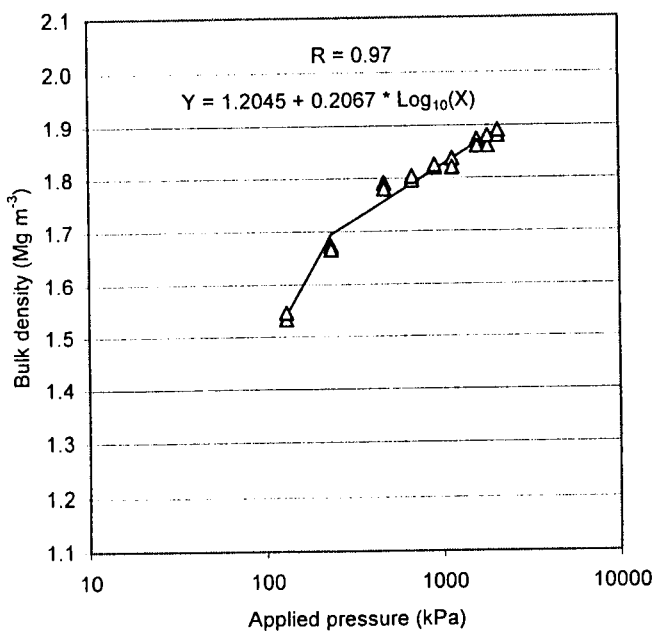
(L2A)



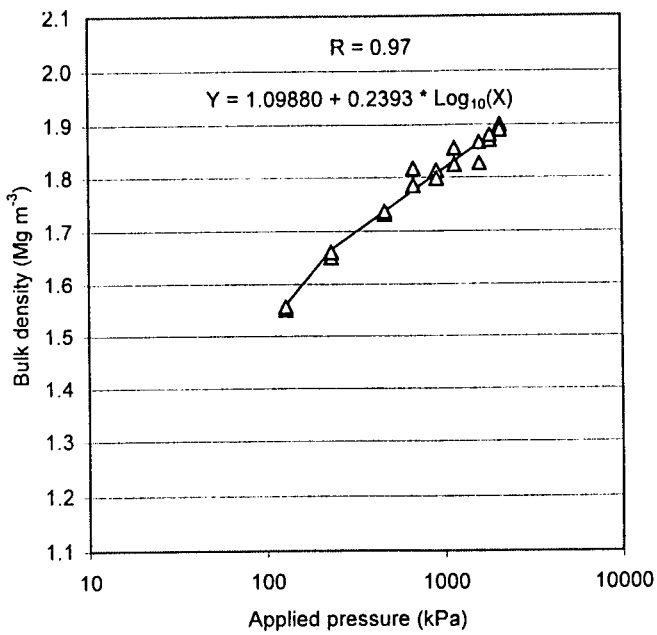
(B1B)



(H1B)

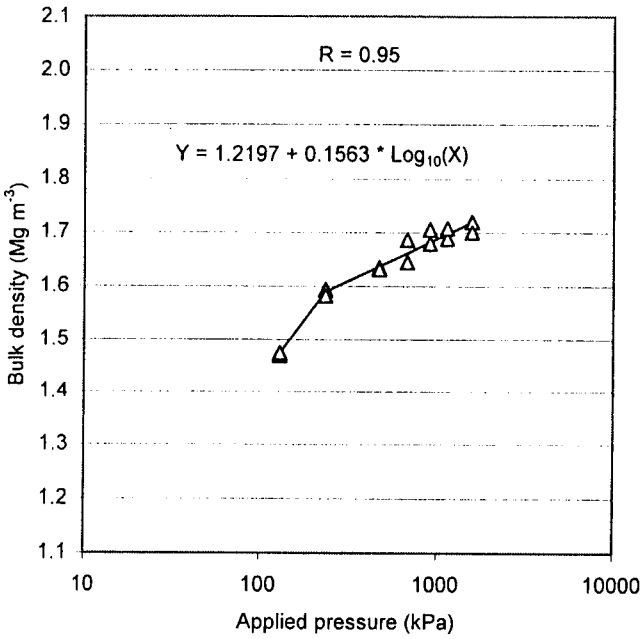


(D2B)

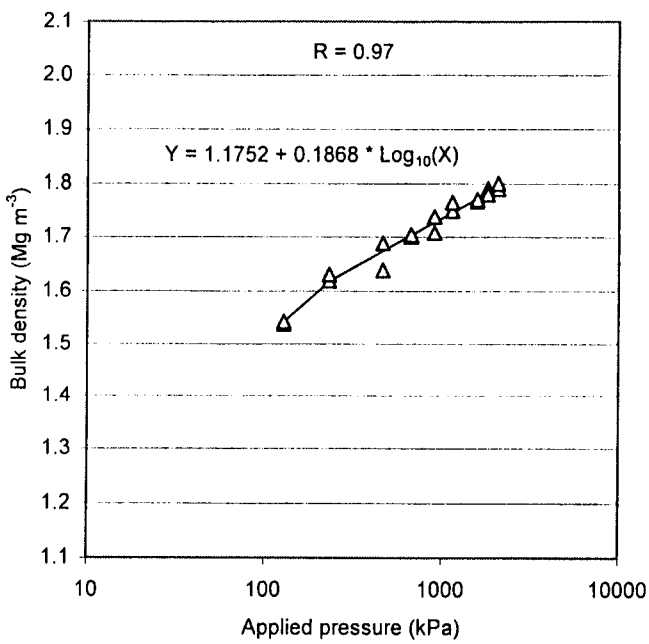


Appendix 5.1: Continued

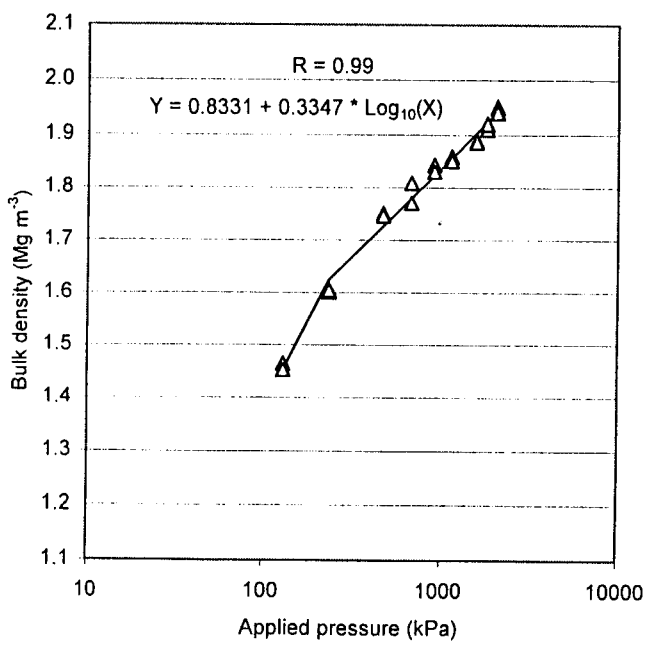
(L1A)



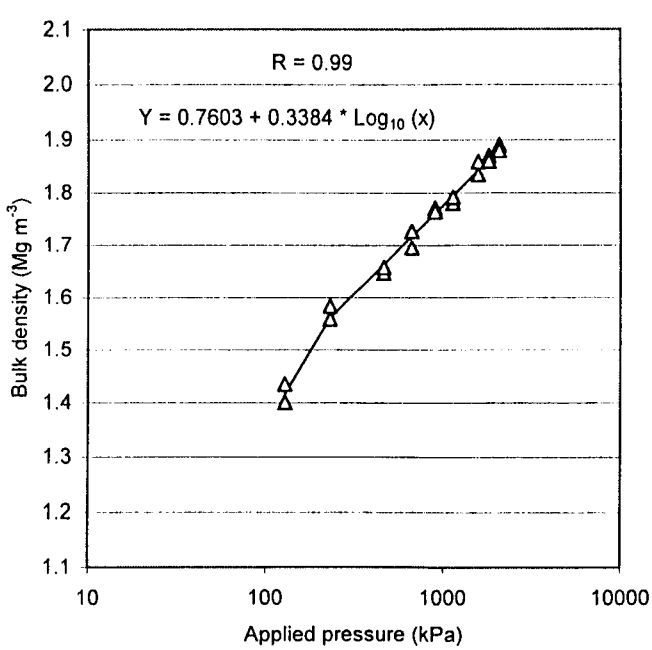
(T2A)



(B3A)

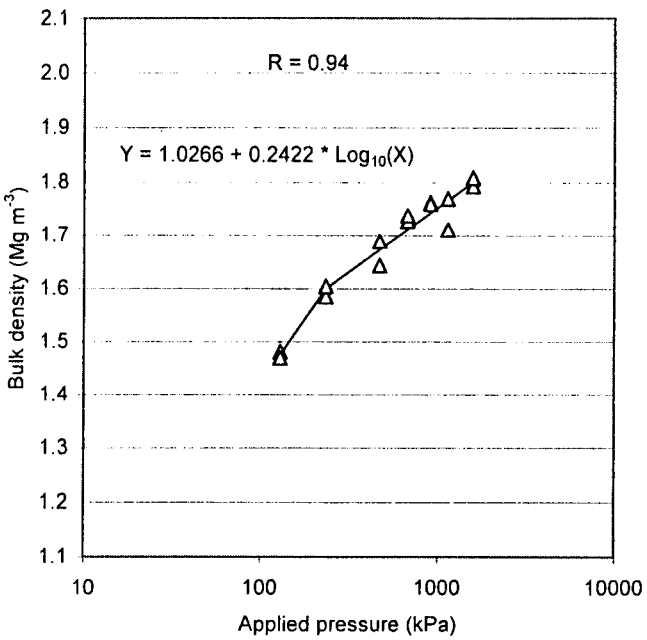


(L3B)

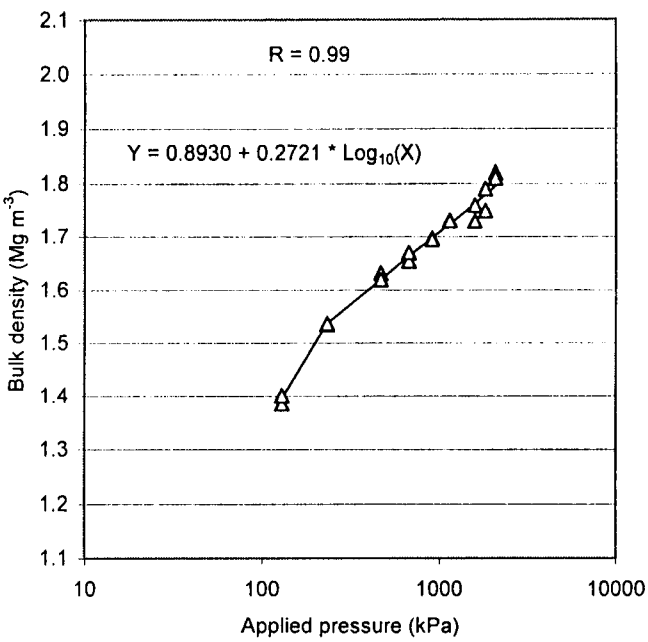


Appendix 5.1: Continued

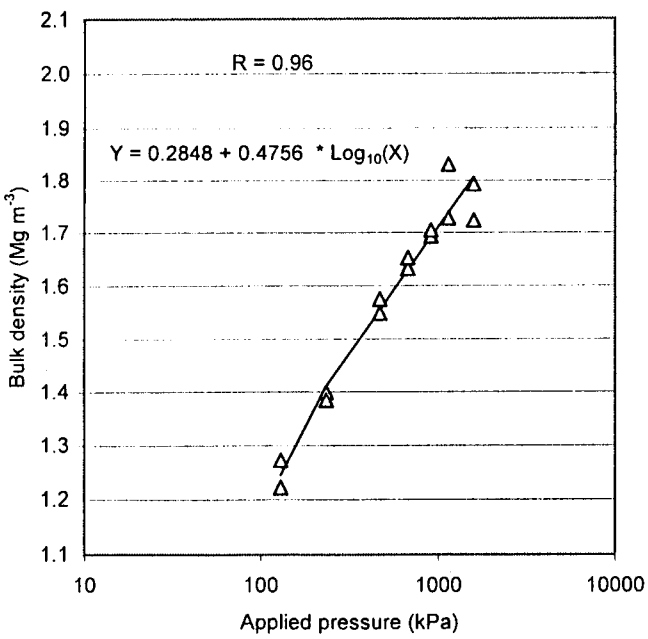
(L1B)



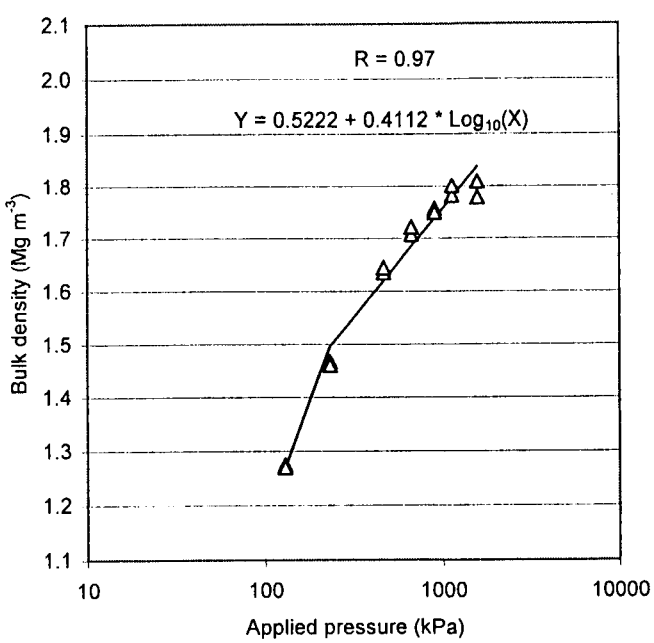
(T1A)



(D3A)

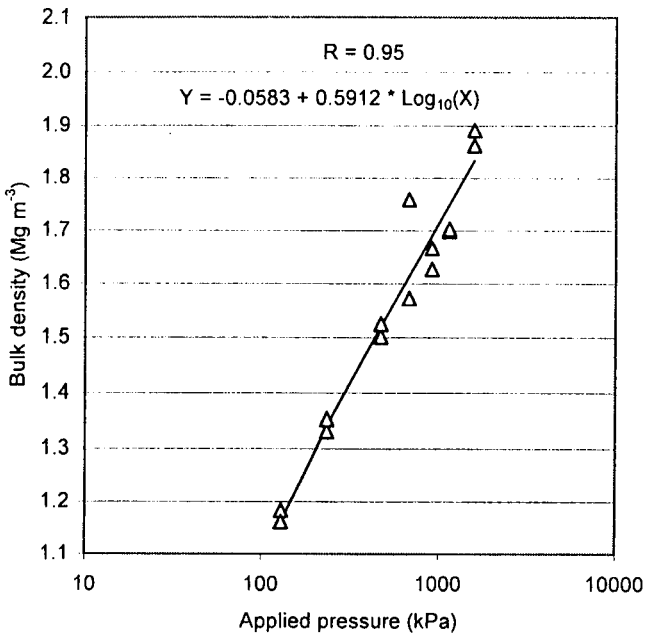


(D1B)



Appendix 5.1: Continued

(D1A)



(G1A)