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EFFECTS OF SOIL COMPACTION BY TRANSPORTATION VEHICLES ON THE SUGARCANE FIELDS OF MUMIAS SUGAR COMPANY

By

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DECLARATION

I declare that this thesis is my work and has not been submitted for a degree in any other University.

Date 28/11/91

Kanali C.L.

This thesis has been submitted for examination with our approval as University supervisors.

Date 28/11/91

Dr. Kaumbutho P.G.

Date 28/11/91

for. Mr. Maende C.M.

DEDICATION

I dedicate this thesis to my grandmothers: Beleta and Mariam.

In appreciation of the roles they have played and continue to play in my life.

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Foremost, I thank God for having kept me alive up to this day and for providing me with an amicable, homely and peaceful working atmosphere.

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ABSTRACT

An investigation of soil compaction in the sugarcane fields of Mumias Sugar Company by transport vehicles was conducted between October, 1989 and April, 1990.

Studies were conducted for the establishment of safe axle loads beyond which detrimental soil compaction would be induced. The treatment involved running a loaded test vehicle in strips previously chosen at random in a split-split plot experimental design. Safe loads were established on a set critical bulk density and by testing the level of significance of the difference in induced soil compaction between treated from non-treated sections.

It was difficult to establish a critical bulk density but the statistical approach produced realistic results. The treatment loads were set slightly higher than the average axle loads induced by trailers of Mumias Sugar Company.

Single bundle and high capacity bin-type trailers were found not to induce detrimental soil compaction. Some nucleus estate trailers however caused significant soil compaction particularly in lowland fields.

Working under soil moisture of 17 to 21% (wet weight), safe loads were found to be payloads of about 9000 and 6770 kg carried by single bundle and nucleus estate trailers (respectively) on 18.4x30 tyres. This corresponded to ground pressures of about 150 kPa.

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LIST OF ABBREVIATIONS

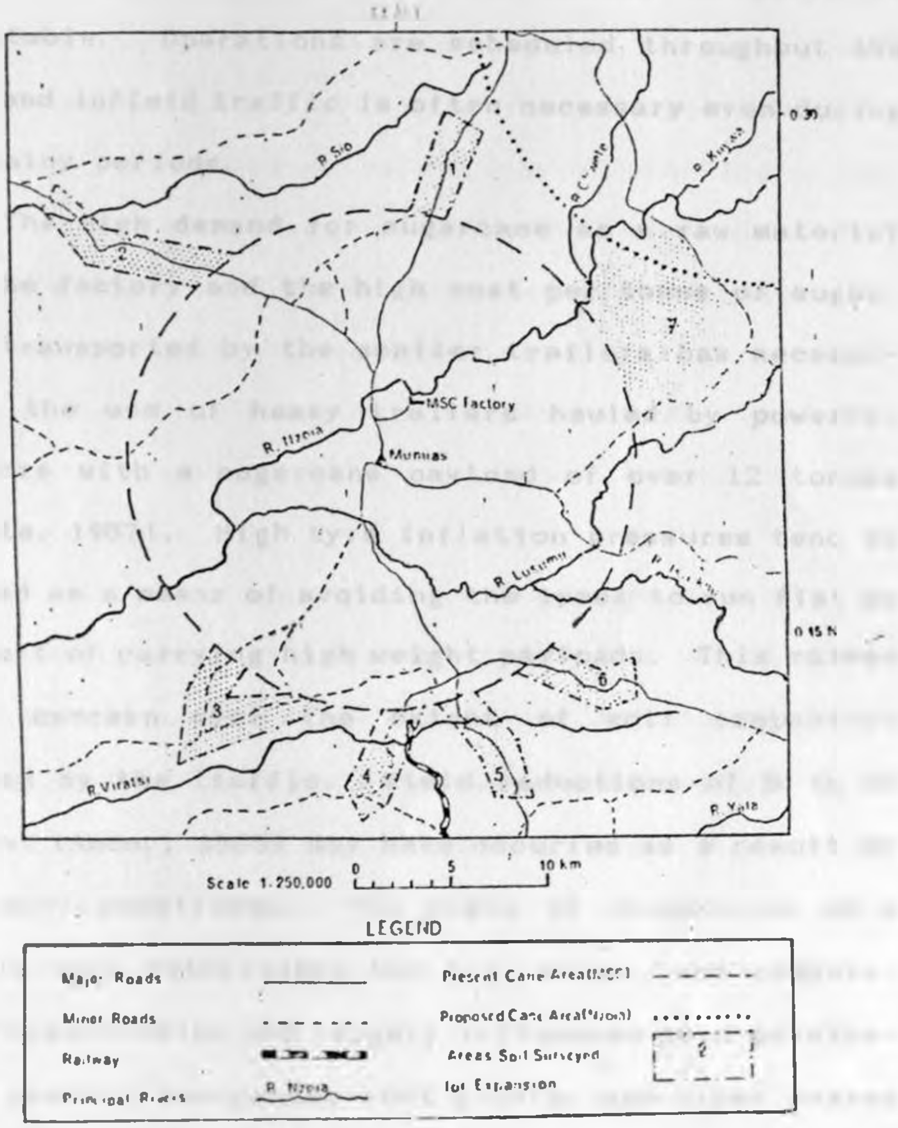
1	b.d	bulk density
2	psi	pounds per square inch
3	kPa	kiloPascal
4	%	percent
5	g/cc	grammes per cubic centimetre
6	SBT	Single Bundle Trailer
7	NET	Nucleus Estate Trailer
8	HCBT	High Capacity Bin Trailer
9	2WD	Two Wheel Drive
10	4WD	Four Wheel Drive
11	wt	weight
12	Same S 80	Same Saturno 80
13	Same E 80	Same Explorer 80
14	Same C 75	Same Centauro 75
15	g	grammes
16	g/cm^3	grammes per cubic centimetre
17	m.c	moisture content
18	i.e	that is
19	km/h	kilometres per hour
20	OMC	optimum moisture content
21	Std Dev.	standard deviation
24	cm	centimetre
25	w(%)	percentage by weight
26	kN	kiloNewtons
27	m	metre
28	m/s	metres per second

1. INTRODUCTION

Mumias Sugar Company (MSC) is the largest sugar manufacturing project in Kenya producing over 50% of the country's sugar. It is located in the Kakamega District of Western Province. MSC has been operational since 1973 and sugar production has increased from 80 to 350 tonnes of sugarcane crushed per hour in the 17 years of existence.

The area on which Mumias Sugar Scheme covers is what is known administratively as Mumias Division and parts of Butere Division, both located in Kakamega District, (see Figure 1). The soils of Mumias drain easily, apart from a few areas of the Nucleus Estate in units 3 and 4 which have poorly or very poorly drained soils, (see Table A1 in Appendix 1). The soils in Mumias and Butere are classified as high potential soils. They are a mixture of dark-brown sandy loams, yellow-red sand and dark-red friable clays. Although the land is well drained and rolling, the Nucleus Estate covers areas that were marsh and have colluvial soils (Wambia, 1979).

Sugarcane for the factory is supplied by local farmers who have contracts with the company under the Mumias Outgrower Scheme and also from the Nucleus Estate (company owned fields). Consequently many fields far from the factory (up to a radius of 30 km) are planted with sugarcane. With the wide area of



Source: East African topographical maps, Y503 Series, sheets NA-36-15 and 16.

Fig. 1. Location of soil surveyed areas for Mumias Sugar Company expansion.

sugarcane fields which in 1984 covered 3370 and 30200 hectares for the Nucleus Estate and Outgrower farms respectively, variations in the nature of soils is inevitable. Operations are scheduled throughout the year and infield traffic is often necessary even during the rainy periods.

The high demand for sugarcane as a raw material for the factory and the high cost per tonne of sugarcane transported by the smaller trailers has necessitated the use of heavy trailers hauled by powerful tractors with a sugarcane payload of over 12 tonnes (Matete, 1987). High tyre inflation pressures tend to be used as a means of avoiding the tyres to run flat as a result of carrying high weight payloads. This raises great concern over the extent of soil compaction induced by the traffic. Yield reductions of 5 to 10 percent (Anon., 1985) may have occurred as a result of poor soil conditions. The state of compaction of a soil largely establishes the air, water, and temperature relationships and largely influences seed germination, seeding emergence, root growth, and other phases of crop production.

The need for higher yields, on one hand, has been met by improvements such as surface drainage, weed and pest control, breeding of resistant crop cultivars and the use of organic fertilizers such as filter-mud. On the other hand large and wide tyre sizes are used to reduce ground contact pressures. Further, normal land preparation after the last harvest on a field reduces the effects built up due to soil compaction. However it cannot be ruled out that traces of accumulated effects of compaction (especially in subsoil zone) still persist. In addition, the random preparation of furrows in the fields poses chances of planting a new crop on a soil that has had extensive compaction.

The design, selection, and management of sugarcane transport vehicles and equipment for tillage must be directed towards causing soil compaction that does not restrict the development of the plant throughout the production cycle.

By and large, compaction of sugarcane fields as a result of transport vehicles is evident at Mumias. There is concern by the Research and Development Section of MSC, that without reduced soil compaction, appropriate agronomic conditions for sugarcane growth will go lacking and the yields may drop so much that the existence of the company may be at jeopardy. Further more, measures to be taken to ameliorate the soils, for example by deep ripping are expensive.

The magnitude and nature of research conducted at Mumias Sugar Company is not sufficient for assessing the soil compaction impact and implications for machinery selection under the prevailing field conditions of Mumias. A research project on agricultural soil compaction at Mumias would enable, the company to gather information on the extent and effects of soil compaction. The project would perhaps make soil compaction effects be appreciated. Measures would be taken to correct any effects already caused while also trying to prevent any more, high levels of soil compaction.

Based on the above report and realisations, a research study was conducted with the following objectives:

1. To compare the levels of induced soil compaction between sugarcane fields with and without the experience of infield use of transportation vehicles.
2. To establish the safe axle loads for Mumias soil conditions considering ground contact and tyre inflation pressures.
3. To select and recommend trailer units that would be unlikely to cause detrimental soil compaction based on the established safe axle loads and ground pressures.

2. LITERATURE REVIEW

2.1. Soil Compaction

Many studies on compaction of agricultural soils due to infield use of vehicles have been conducted all over the world (Dias and Nortcliff, 1984; Taylor et al., 1986; Schuler and Lowery, 1986; Bashford et al., 1987; Gunjal et al., 1987; Dexter et al., 1988 and Ellwein and Froelich, 1989). This is because there has been an increasing concern about the effects on the soil of the present-day heavy and powerful field vehicles. Attempts at analyzing soil compaction effects on the agricultural soils of Kenya seems to be lacking. This is perhaps because there is lack of general awareness of the effects compaction may have on the soils, and heavy field vehicles are not very common except in large scale oriented industries such as the sugar industry.

2.1.1. Soil Response to Machinery

Soil response to machinery is known to be a function of traffic parameters, soil properties and soil moisture content at time of traffic. Response is usually described in terms of changes in dry bulk density, porosity and/or penetration resistance as functions of applied pressures and soil moisture content (Raghavan et al., 1989).

A review by International Soil Tillage Research

Laboratory (ISTRL) Volume 1 (1981) reported that vertical forces due to wheel slip are transmitted by the tyre to the soil. The inflation pressure, size and tyre carcass strength control the distribution over the area of contact with the soil, which is influenced primarily by the initial soil strength. The forces at the tyre-soil interface and the initial soil strength control the magnitude and distribution of stresses in the soil beneath the wheel. These stresses and the compactibility of the soil determine the kind and amount of soil strain.

According to Ellwein and Froelich (1989) tillage resistance was 60 to 90% higher in the wheel-tracked areas of combine harvesters and tractor transport units as compared with no wheel tracks. Because compacted soil is more dense and hard, wear on tillage tools and tractor tyres may be increased as well.

Another review by ISTRL Volume 2 (1982) reported that heavy tractors (3 to 5 tonnes) caused significant soil compaction especially on fine-textured soils when wet. It was recommended that axle loads be limited so that no compaction causing significant yield decreases occur deeper than 40 cm.

During wheel load studies there is first, the influence of load on the average contact pressure. Increase of tyre deflection and sinkage as load increases corresponds to increase in average contact pressure which is a non-linear function of tyre and soil properties. Second, at high loads soil responses may be related to a greater extent with the load per se than contact pressure (The ISTRL Review Volume 1, 1981).

On Minnesota soils having 32 to 38 percent clay, axle loads greater than 9.9 tonnes and surface pressures of 173 kPa (25 psi) caused compaction up to a depth of 60 cm when the soil under traffic was relatively wet (Ellwein and Froelich, 1989).

Within certain field conditions the induced soil compaction becomes significant beyond certain contact pressures (ISTRL Volume 1, 1981). In Hawaii vehicles having a contact pressure up to about 30 kPa showed little influence on saturated hydraulic permeability (50 mm/h reduced to 48 mm/h), whereas a vehicle having a contact pressure of 92 kPa reduced the permeability to 3 mm/h. A 101 kPa pressure produced a maximum change in bulk density of 0.24 g/cm^3 (at 70 to 170 mm depth) compared with only 0.16 g/cc (at 170 to 200 mm depth) for a 40 kPa pressure.

Taylor et al. (1986) could not disprove of the fact that subsoil compaction is not affected by mean ground pressures as the test was limited to one soil condition (for each soil used), and the soils were relatively soft and dry.

Increase in tyre section width or diameter as load increases does not necessarily control soil compaction as the average contact pressure is held constant (ISTRL Volume 1, 1981). This is because at a given constant pressure, stress within the soil will extend considerably deeper for wide tyre carrying a high load than the narrow tyre with a low load. In practice the most usual response to the need to carry higher loads on tyres has been an increase in inflation pressure with relatively small or no increase in section width.

Wide section front tyres and trailer tyres together with dual rear tyres for tractor pulling slurry tankers have been found to be essential for spreading operations on soft soils with a high water table (ISTRL Volume 2, 1982). The tyres are also useful in maintaining mobility and preventing excessive sinkage. With row crops the use of wide low pressure tyres or duals may not be satisfactory if the wheel tracks pass over or close to the planting row.

The review by ISTRL Volume 1 (1981) stated that the type of response to multiple passes will depend markedly on the initial soil strength and its distribution with depth. Similar observations were made by Bashford et al. (1987) and Burger et al. (1983). A loose soil shows much larger increases in compaction during the first pass than in subsequent passes. Soils with appreciable initial strength will have a first pass compaction which will differ little from that of subsequent passes.

In weak soils the zone of maximum compaction occurs far below the wheel rut (ISTRL Volume 1, 1981). However, in stronger soils such as sandy loams and clay loams having a dry bulk density greater than 1.1 g/cm^3, most of the compaction may be near the surface.

Humbert (1968) reported some work on the effects of compaction at different moisture levels on porosity and air percentage by volume. As the apparent density increased to the critical density, the total pore space decreased to slightly less than 50%. The air percentage by volume decreased rapidly to about 10% as density increased to the critical level. It is commonly accepted that changes in bulk density, pore size distribution and aggregate stability result in changes in soil aeration. These factors affect the interchange of oxygen and carbon dioxide between the soil and the atmosphere.

Burger et al. (1983) reported that soil moisture content significantly affected the actual change in soil compaction. At moisture contents above the Proctor optimum for compaction, wheel slip can contribute to compaction as significantly as loading (Raghavan et al., 1989). At high slips, topsoil structure is damaged by smearing. Deep ruts and sideways displacement of soil due to greater sinkage is also a problem at high moisture contents.

The degree of curvature around the peak of the Proctor curve can be used to decide a probability range for soil moisture estimation (Raghavan et al., 1989). The sharper the peak, the more critical the accuracy of the estimate of moisture content tends to be near the optimum at usual times of traffic. Optimum curves can serve as guidelines for estimating critical soil compaction limits in terms of yield for expected climatic conditions. Optimum curves expressed as yield versus degree of compactness could, by way of models be expressed in terms of yield as a function of sequences of operations, i.e. in terms easily interpreted at the farm level.

Several authors have reported that the pressure in the upper soil layer is described by mean ground pressure and soil deformation. Subsoil compaction on the other hand is largely a function of total load carried and is much less affected by the mean ground pressure (Taylor et al., 1986; Schuler and Lowery, 1986; Froehlich, 1934; Soehne, 1953; Taylor et al., 1980 and Hakansson et al., 1981).

The review by ISTRL Volume 1 (1981) also reported that the zone of maximum compactness tends to approach the surface with repeated passes. It was stated that greater attention should be paid to the vertical and horizontal distribution of changes in the soil properties during compaction of field soils. However, this might require sensitive methods of measuring soil compaction like the use of pressure cells which are sometimes cumbersome to put in the soil especially where a large amount of data is required.

Subsoil compaction, which is mainly caused by use of tyres requires greater effort to eliminate by ripping than surface compaction (Bashford et al., 1987). In addition they noted that the resulting effect of small differences in bulk density resulting from cumulative trafficking, when accumulated over a long span of time is not known but could be detrimental to the soils.

The present study takes keen concern on both surface and subsurface soil compaction because more than one harvest is obtained out of one crop of sugarcane. In all these harvests the crop is carried out of the field using heavy transport vehicles which result in both surface and subsurface soil compaction. Depending on the depth of compaction, surface soil compaction may not be completely ameliorated by inter-row cultivation and any other tillage operations carried out afterwards. As a result the crop may suffer because of the induced unfavourable soil conditions.

A soil which is exposed to extensive compaction experiences low infiltration rates, a high runoff and increased soil erosion rates (Raghavan et al., 1989).

The review by ISTRL Volume 2 (1982) also reported that permeability of a hidrol-humic latosol in Hawaii below 30 cm was 160 mm/h before ploughing and 57 mm/h after ploughing with a loaded wheel running in the furrow bottom.

Reduced permeability in wheel ruts has been observed to lead to water erosion problems (ISTRL

Volume 2, 1982). Additionally, the review stated that ploughing land which has previously been subjected to sufficient wheel traffic to increase its bulk density and/or aggregate size can produce some degree of wind erosion control.

Compaction will reduce soil permeability and the opportunity to remove excess water by drainage may diminish (ISTRL Volume 2, 1982).

Compaction-induced changes in the air-water regime affect microbial activity such that the nitrogen balance favours ammonium over nitrate nitrogen as compaction levels increase (Raghavan et al., 1989 and Schuler and Lowery, 1986).

2.1.2. Crop Response to Compaction

Higher mechanical impedance of compacted soils restricts the depth of root penetration as well as the overall root density, which implies slower root development (Raghavan et al., 1989). Similar observations were reported by a review of the ISTRL Volume 2 (1982). This leads to a reduced access to water and nutrients.

The review by ISTRL Volume 2 (1982) also reported that root distribution of maize was found to be closely associated with both the number of passes and the contact pressures of the tyres running over the soil either before or after seeding. The depth to which dense rooting extended was 90 cm in the absence of traffic at sowing whereas for 1, 5 and 15 passes of a wheel with a contact pressure of 62 kPa dense rooting was restricted to 60, 45 and 25 cm respectively.

Plant growth and yield are likely to show optimum responses at certain level of soil compactness (ISTRL Volume 2, 1982). The position of the optimum however is related to soil type, crop growth stage and climatic conditions.

The review by the ISTRL Volume 2 (1982) further reported that heavy traffic prior to or during seedbed operations for wheat, sorghum and maize did not decrease the yield; in some cases there was an increase as a result of better continuity of water filled pores, leading to better plant establishment. Similar observations were made by Gunjal et al. (1987).

Compaction caused emergence of maize to be delayed in the first growing season and plant height differences to be large (Schuler and Lowery, 1986). The delay also increased with increased compacting load. They attributed the delay to the larger surface soil clods resulting from compaction.

Ellwein and Froelich (1989) reported that research in Sweden indicated that it took six to seven years for recovery of an initial crop loss from 11 tonne axle load on a 40% clay soil, and an initial crop yield reduction of 30% had not been recovered after seven years on a 70% clay soil. Additionally, research in Indiana (USA) on subsoil compaction of silt loam soil showed a 55% reduction in maize yield during the first year due to a 6% increase in soil density, and a 23% yield reduction the following year. Crop yield reductions ranging from 5 to 10% were due to axle loads as low as 5 tonnes, although such compaction and less can usually be alleviated through normal tillage operations.

2.2. Measures of Controlling Soil Compaction

Soane (1985), and Soane and Boone (1986) suggested that new indices be developed to provide stronger links between traffic-soil and soil-plant interactions. Efforts in this direction have been made by Ellwein and Froelich (1989), Dias and Nortcliff (1984), and Trouse and Humbert (1968) who came up with recommended cone index and bulk density values for various soils (see Tables 2.1 and 2.2).

Trouse and Humbert as reported by Humbert (1968) studied root distribution in principal sugarcane soils compacted from 0.69 to 1.89 g/cm^3. Radioactive rubidium was placed in the centres of the compacted cores which were then placed in pots of the same soil type, and planted with sugarcane. The effectiveness of root systems in compacted soil was measured by the rate at which the rubidium was removed. Critical levels of soil compaction were established in terms of soil density, a measurement which may be easily determined in the field. When operations of heavy equipment cause puddling and compaction beyond these

Table 2.1. Cone indices and ground pressures (kPa) at which sugarcane development is affected

	Field condition	A	B	C
1.	Field capacity	1380	2090	-
2.	Relatively wet	-	-	40 to 50
3.	Moist	-	-	80 to 100
4.	Dry	-	-	200 & above

A = cone index value that causes reduced root growth,
B = cone index value that causes reduced yield, and
C = recommended ground contact pressures.

Table 2.2. Dry bulk densities (g/cm^3) at which sugarcane root development is affected

	Soil type	A	B	C
1.	Silt loam	-	-	1.40
2.	Alluvial	-	-	1.55
3.	Low humic latosols, (surface) [Ferralic CAMBISOLS, Appendix 2]	1.06	1.21	1.58
4.	Low humic latosols (subsoil)	1.05	1.20	1.51
5.	Hydrol humic latosols (surface)	0.60	0.74	1.10
6.	Grey hydromorphic clay (surface)	1.21	1.30	1.76
7.	Grey hydromorphic clay (subsoil)	1.05	1.14	1.74
8.	Silt clays	1.05	1.24	1.58

A = bulk density at which roots grow normally,
B = bulk density at which roots become flattened, and
C = bulk density at which roots are restricted.

Source: Trouse and Humbert (1968), root studies in Hawaii; Ellwein and Froelich (1989) and Dias and Nortcliff (1984).

critical levels, corrective measures are required to restore the soils to a satisfactory tilth.

In the absence of satisfactory reconditioning, yields suffer a decline in the subsequent ratoon crop.

In order to make use of the recommended critical bulk density values one must clearly classify and name appropriately the soils in which a test is conducted.

A review by The ISTRL Volume 2 (1982) recommended that for heavy trailers with axle loads up to 160 kN the compaction in the subsoil could be reduced by using a tandem axle. The review concluded that to reduce incidence of compaction it would be desirable to reduce average ground pressures of tyres on the field below 200 kPa (29 psi), and preferably below 100 kPa (14.5 psi). In the case of load-carrying vehicles this would result in a considerable increase in the cost of the running gear.

Large contact area of a track, as compared to a tyre, has a potential of reducing soil compaction resulting from use of large agricultural tractors (Bashford et al., 1987).

An alternative that is presently receiving more attention is that of controlled traffic (Raghavan et al., 1989). The concept behind this approach is that a small percentage of the total field area is devoted to machinery traffic with energy advantages from the point of view of traction, while the rest of the field is never compacted.

2.3. Economic Considerations

The total economic impact of soil compaction is difficult to assess due to the vast number of interrelated factors involved (Raghavan et al., 1989). Diseases, soil fertility, variety of crop, weather (climate), drainage and soil structure (compaction) are some of the factors that affect development of a crop and the resulting yield.

Economic impact may be assessed in terms of yield reductions; higher fuel costs in tillage; higher runoff and erosion rates; higher operational costs of irrigation due to poor infiltration and presumably, higher evaporative losses, on compacted soils; wear and tear and breakage of tillage tools in compacted soils; less efficient use of fertilizers and future costs of restoring soil structure (Raghavan et al., 1989).

Optimum tractor size depends on crop and weather conditions and small tractors are not necessarily better if traffic intensity (percentage of area covered) is taken into account (Gunjal et al., 1987) and (Raghavan et al., 1989). This however, does not consider the long-term cumulative effect of subsoil compaction.

2.4. Methods of Measuring Soil Compaction

Dry bulk density and penetration resistance are generally accepted as good indicators of soil compaction (Raghavan et al., 1989).

2.4.1. Dry Bulk Density

Dry bulk density is defined as the weight of mineral matter divided by the volume of the entire element (Lambe and Whitman, 1979).

Core and excavation are direct methods and require removing and weighing the soil from a known or measured volume. Bulk density is related to the attenuation and scattering of nuclear particles passing through soil. With proper calibration these indirect methods can be used to estimate soil bulk density (Erbach, 1987).

The core method employed in this study usually uses a cylindrical metal sampler that is pressed or driven into the soil to desired depth and is carefully removed to preserve a known volume of soil as it existed in situ (Erbach, 1987).

The San Dimas soil core sampler is hand operated with a rotary cutter around a stationary collector tube (Andrews and Broadfoot, 1958).

The Kachinskii method (Revut and Rodes, 1969) uses cylindrical rings that are pressed into the soil. The cutting edge of the rings are chamfered from the outside. The inside of the cylinder is relieved above the cutting edge to eliminate distortion of the soil sample caused by friction with the cylinder walls.

Wells (1959) developed a core sampler consisting of a sampling tube and trimming ring that can be driven into the ground with a heavy hammer. A hollow shafted borer slips over the sampling tube and is turned by hand to remove the surrounding soil. The sampler takes a 5 cm core and can sample to 120 cm in steps of 15 to

30 cm. He found little soil disturbances across the core but there were some problems with compression of the core.

Foale and Upchurch (1982) described a hand operated device for taking cores of 20 to 50 mm diameter to depths of 2 m. The system uses a drop hammer or electric jack hammer for driving the corer and a ladder jack for removing the corer.

2.4.2. Cone Index

Attempts have been made to relate cone index, the force per unit base area required to push a penetrometer through soil, to soil density. Ayers and Perumpral (1982) as reported by Erbach (1987) developed Equation 2.1 to predict soil density from cone index and soil moisture content.

$$p_d = [(CI/C_1)C_2 + (MC-C_3)^2]^{1/C4} \qquad ..... \; 2.1$$

where:

p_d = dry bulk density (g/cm^3),

CI = cone index (kPa),

MC = moisture content (% dry weight), and

C_1, C_2, C_3 and C4 are constants that depend on the soil type

Gameda et al. (1989) developed a relationship between soil strength and structural parameters for a clay soil consisting of 72% clay, 22% silt and 6% sand, (see Equation 2.2).

$$(K/CI) = A\,(p_d/p_s)^n\,e^{b\Phi} \qquad \ldots\ldots 2.2$$

where:

CI = cone index (kPa),

K = bulk modulus (kPa),

p_d = dry bulk density (g/cc),

p_s = soil particle density (g/cc),

Φ = soil moisture content (% dry weight), and

A, b and n are soil constants dependent on moisture and texture.

A relationship between cone index and bulk modulus would allow for the in situ determination of material properties for layered, non-homogeneous soils. The results were however restricted to one soil type. In order to develop comprehensive models, further studies needed to be conducted to account for different soil strengths prior to compaction, the influence of soil textural properties, and the effect of layered soils (Gameda et al., 1989).

Sands et al. (1979) found that for a sandy soil, resistance to penetration was largely independent of water content and was directly related to soil bulk density. At constant bulk density, penetration resistance increased with depth because of an increase in overburden pressure and a decrease in organic matter content. Chesness et al. (1972) found that remoulded soil samples do not exhibit the same characteristics as in situ soil and concluded that bulk density and soil moisture content are not sufficient to describe penetration resistance in field sandy loam soils.

2.5. Studies on Soil Compaction at Mumias

The Mumias Sugar Company Agricultural Services Annual Report of 1987/88 indicated that 47.8% of sugarcane is delivered to the factory by the company fleet, 47.6% by contractors and 4.6% by others. In order to haul in excess of a 45% quota, some contractors have fleet capacities which are excessively high, (up to 12 tonnes payload) on a single axle trailer.

Dry bulk densities of up to 1.81 g/cm^3 were obtained within the wheel track of such a trailer during a preliminary study of this project on a sandy clay loam soil. Uncompacted sections recorded a dry bulk density value of 1.67 g/cm^3. An earlier study on soil compaction at Mumias (Anonymous, 1985) subjectively reported a sugarcane yield loss per crop of 5 to 10% attributable to soil compaction. However, the yield loss may also have resulted from cane stool destruction as the transport vehicles normally trample on them.

Drew (1972) in a report on Cane Transport Trials at Mumias reported some minimum ground contact pressures. He recommended that the pressures be kept below 104 kPa on the soils of Units 3 and 4 and 173 kPa on the soils of Units 1 and 2 (see Table A1 in

Appendix 1). However, he did not make reference to the moisture contents in the fields.

The acceptable pressures would probably be related to the soil type, soil moisture content, the crop grown and the number of passes. Therefore more extensive onsite tests need be conducted at Mumias under wet soil moisture conditions where compaction is likely to be maximised.

Observation on traffic movement in the fields shows that on the Nucleus Estate, traffic is generally restricted to the inter-row and trampling damage to stools is limited. Compaction may be significant in the inter-row but it should not affect the root zone and it can be relatively relieved by inter-row deep ripping. In the outgrowers farms, the failure to control infield traffic movement has been a problem for many years and no satisfactory solution has been found to date. Awareness amongst farmers on the damage caused to sugarcane and soil may lead to consideration in regulating traffic movement.

The major impetus which led to this topic and the objectives therein for study are the recommendations by Kamau (1988). The study compared the bulk densities and cone index values in tracked and untracked sections travelled by a twelve tonne trailer. The study, however, did not record any results pertaining to the magnitude of the axle loads, ground contact pressures and tyre inflation pressures beyond which compaction would be regarded as being detrimental to the soil structure. In addition the study was limited to a narrow range of moisture and soil conditions.

Kamau (1988) found that there was a significant difference between field sections travelled by a twelve tonne single axle basket type trailer and the untracked sections. The study reported a recommended maximum ground contact pressure of 152 kPa for Mumias Sugar Zone. However, Kamau found no practical justification for this pressure. He further reported that single bundle and nucleus estate trailers exerted ground contact pressures of 180 and 207 kPa respectively while the twelve tonne basket type trailer exerted a pressure of 318 kPa, a value which is more than twice the maximum recommended for Mumias sugar zone.

3. THEORY OF SOIL COMPACTION

Soil compaction may be defined as the compression of a mass of soil into a small volume (Raghavan et al., 1989). Changes in bulk properties are accompanied by changes in structural properties, thermal and hydraulic conductivity and gaseous transfer characteristics. This in turn affect chemical and biological balances.

Because of the highly complex character and almost infinite variability of soils and of the natural and man-imposed forces acting on soils, understanding the soil compaction process is quite challenging to both the practical farmer and the researcher. Many factors such as soil type, moisture content, load rate and magnitude, vehicle and type of running gear affect soil compaction. A clear understanding of the mechanics of soil compaction however, is necessary if soil compaction is to be minimized. To enhance the understanding, models and empirical equations continue to be formulated by researchers studying soil compaction.

3.1. Description of the Compaction Process

Barnes et al. (1971) reported that when a soil is subjected to an applied load that is sufficient to cause a volume change, there are four possible factors to which the change could be attributed. These factors are: a compression of the solid particles, and of the liquid and gas within the pore spaces; a change in the liquid and gas contents in the pore spaces, and rearrangement of the solid particles.

3.1.1. Compression of the Solid Particles

Barnes et al. (1971) reported that when an external force is applied to a partly saturated soil element, liquid is displaced from between the particles and the contact area between the particles increases. The increase in contact area depends on the deformation of the soil particles. The deformation is usually assumed to be elastic in nature and the soil particles will rebound upon release of the applied load. A stress-strain relationship, as determined for metals where stress is directly proportional to strain until the elastic limit, has not been developed to describe the deformation of the individual soil particles. The general stress strain law for other materials would probably apply; however, the moduli of elasticity for different soil mineral particles would have to be determined. The applied load in most cases is larger than any surface tension forces that exist in the soil-water interface.

3.1.2. Compression of the Liquid and Gas within the Pore Space

A liquid may be considered incompressible for most engineering problems unless it is subjected to sudden or large change in pressure. Compressibility can be expressed in terms of the bulk modulus of elasticity, defined as the ratio of increase in pressure to decrease in volume. For a given volume V of liquid subjected to a change in pressure:

$$\delta V = - V \, \delta P / k \qquad \text{.....} \; 3.1$$

where:

k = bulk modulus of elasticity (Pa),

δV = change in volume of liquid (m^3), and

δP = change in pressure (Pa).

As a liquid is compressed, its resistance to additional volume change increases. The change in volume of water can be disregarded as affecting soil compaction for practical purposes. This conclusion is supported by tests conducted by Hovanesian (1958) in determining a relationship between mean stress and changes in bulk density.

The relationship shown in Equation 3.2 based on perfect gas laws, between pressure and volume change is valid at constant temperature for air present in the soil element.

$$\delta V_g = (RT/(P+\delta P) - V_g \qquad \text{.....} \; 3.2$$

where:

V_g = volume change of air in pore space (m^3),

R = universal gas constant, and

T = absolute temperature (K).

The difficulty in using this relationship is determining the magnitude of the pressure acting on the gas in the pore spaces.

3.1.3. Rearrangement of the Soil Particles

Rearrangement of the soil particles depends on several factors. The change in state of compaction depends on movement of either the liquid or the solid phases, or both. This is because the solid and the liquid phases are relatively incompressible and do not undergo appreciable volume change under loads usually applied to the soil mass. For unsaturated granular soils volume change is due to soil particles changing positions by rolling or sliding. In a saturated condition, the controlling factor for a large volume change is the rate at which liquid moves within the soil mass and, to a limited degree, from the soil. For fine-grained, partly saturated soils, composed predominantly of clay, the volume change depends upon reorientation of the particles and displacement of the water molecules between particles. In a saturated state, water movement plays an important role as very little volume change occurs by compression of water.

The movement or rearrangement of the soil particles depends on the structural arrangement of the particles and in fine-grained soils, on the degree of bonding between adjacent particles. The change in state of compaction resulting from rearrangement of the particles is due primarily to a change in the volume of the voids. The empirical relation (see Equation 3.3) as reported by Barnes et al. (1971) has been determined from uniaxial compression tests in the general field of soil mechanics to show the variation of soil void ratio with applied load.

$$\epsilon = \epsilon_0 - c \log P/P_0 \qquad \text{..... 3.3}$$

where:

ϵ = the void ratio due to applied pressure P,

ϵ_0 = the void ratio at initial pressure P_0 and

c = slope of the curve on semilogarithm plot.

Soehne (1958) determined that for arable soils compaction could be described by the relationships in equation 3.4.

$$n = -A \ln P + C \qquad \text{..... 3.4}$$

where:

n = porosity,

C = porosity obtained by compacting loose soil at a pressure of 69.1 kPa, and

A = the slope of the plotted curve.

From empirical results that have been obtained, the conclusion is that the relationship between change in void volume and externally applied load is not linear. An exponential or logarithmic function would best describe the relationship. The particle-size distribution will influence the change in void volume mainly because of the rearrangement of soil particles. Well-graded soil containing both coarse and fine-grained particles will have more contacts between particles than will poorly graded soil. Consequently, the resistance to shear-induced motion will be proportionately larger and the change in void ratio for any single load application will be less for a well-graded soil than a poorly graded soil.

3.1.4. Change in Liquid and Gas Contents

Liquid retained by the soil may be forced from between the particles when the soil is subjected to an applied load. The amount forced out into the voids depends upon the magnitude of the load applied, the moisture content of the soil, the type of soil particles, and the bonding forces between liquid and soil particles. If the quantity of liquid displaced does not exceed the capacity of the pore spaces, the liquid is drawn back between the particles by the soil-liquid forces of attraction when the load is released. For saturated conditions at the time the load is applied and for saturation resulting from liquid displacement, volume change is a function of liquid movement.

The pressure generated in the pore liquid affects compaction. In confined saturated soils external loads are sustained primarily in the liquid phase of the soil. If the volume of liquid is reduced, the hydrostatic stress is transferred to interparticle stress. The amount of stress transferred depends on the quantity of the liquid lost. The hydrostatic pressure influences not only the movement of liquid but also the movement of soil particles to a new position. Volume change is a function of both movements.

3.2. Relations Between Applied Forces and Resulting Compaction

The difficulty of developing a mathematical model that will accurately relate stress and strain without being so complicated as to be impractical has led to the development of empirical equations for describing part of the relationship between the applied load and the resulting volume change. One of the oldest models, the Mohr-Coulomb formula, (see Equation 3.5), relates the stresses acting on a plane through the soil by using the analogy of simple sliding friction. Strain is not included in the relationship; however, the equation may be used to predict failure and thus provide information about one phase of the compaction process.

$$F(\sigma) = c + \alpha(\sigma_1+\sigma_3)/2 - (\sigma_1-\sigma_3)/2 \qquad \ldots\ldots\ 3.5$$

where:

F = stress at failure (Pa),
c = the vertical intercept on the q-axis,
α = slope of the failure surface,

σ_1 = major stress experienced at failure (Pa), and

σ_3 = minor stress experienced at failure (Pa).

In studies of agricultural implements as reported by Bekker (1957) Berstein developed an equation that relates the ground pressure P (Pa) and sinkage z (m) of a given area:

$$P = k z^m \qquad ..... 3.6$$

where:

k = the modulus of deformation (Pa) depending upon the size of loading area and properties of soil,

m = an exponent depending upon the type of soil.

In order to separate the soil properties the cohesional effect, and frictional properties, Bekker (1957) introduced the following expressions:

$$k = k_c/b + k_\phi \qquad ..... 3.7$$

$$P = (k_c/b + k_\phi) z^m \qquad ..... 3.8$$

where:

k_c = a cohesive modulus of deformation,

k_ϕ = the frictional modulus, and

b = the smaller dimension of the loading area.

While this relationship is satisfactory for certain aspects of soil compaction, the equation does not relate force to volume change. Most of the emphasis is on changes in location of a soil-loading plate surface, while the phenomena within the soil as well as the effects of soil variables are included in parameters obtained from empirically designed tests applied to the soil at the location in question.

Brandon et al. (1986) developed the constitutive relationship for a sandy clay soil with a plastic limit of 11.3%, a liquid limit of 22.5% and a moisture content of 10% dry basis, (Equations 3.9 to 3.12).

Elastic part: $0.0\% < \epsilon_x < 0.2524\%$

$$(\sigma_1-\sigma_3)/\sigma_3 = E_i\epsilon_x \quad ..... \; 3.9$$

Plastic part: $\epsilon_x > 0.2524\%$

$$(\sigma_1-\sigma_3)/\sigma_3 = E_t\epsilon_x + (1/\sigma_3)^n \quad .... \; 3.10$$

Unloading portion:

$$(\sigma_1-\sigma_3)/\sigma_3 = E_i\epsilon_x \quad .... \; 3.11$$

Reloading portion:

$$(\sigma_1-\sigma_3)/\sigma_3 = \epsilon_x/\sigma_3(a+b\epsilon) \quad .... \; 3.12$$

where:

a, b = constants determined experimentally,

E_i = modulus of elasticity in kPa,

E_t = tangent modulus or slope in kPa,

σ_1 = axial pressure in kPa,

σ_3 = confining pressure in kPa,

n = the influence factor, and

ϵ_x = axial strain.

The plastic portion of the stress-strain curves was dependent on confining pressure and tangent modulus while the elastic portion was dependent on modulus of elasticity.

Dexter et al. (1988) measured pressure transmission beneath the wheels of moving agricultural vehicles in two soil conditions, (loamy-mixed-thermic and coarse- loamy-carbonatic-thermic). The vertical component of soil pressure was found to decrease more rapidly with depth than predicted by equation 3.13 usually used in soil mechanics. These prompted them to propose other equations like equation 3.14, which provided much better descriptions of the experimental data.

$$\sigma_z / \sigma_m = [1-(R/z)^2]^{v/2} \qquad \ldots\ldots 3.13$$

where:

σ_z = vertical component of pressure (Pa) at depth z,

σ_m = contact pressure (Pa) between the plate and soil,

R = the radius of the plate (m), and

v = stress concentration factor.

Equation 3.14 was developed for the mean maximum peak soil pressures at various depths below the tractor wheels while running in coarse loamy soils.

$$\sigma_z/\sigma_0 = \exp(-z/z_0)^v \qquad \ldots\ldots 3.14$$

where:

σ_0 = maximum pressure at the soil surface (Pa),

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z_0 = an adjustable reference depth at which σ_z/σ_0 is equal to 1/e (m), and

v = an adjustable parameter which, in combination with z_0, describes the rapidity of attenuation of the peak soil pressure with depth.

Equation 3.15 developed by Brandon et al. (1987) does not show a direct relationship between the applied force and the resulting compaction. The model is based on Mohr-Coulomb failure criteria. It was found that simulated data compared fairly well with experimental results, except that there was a tendency of over-prediction at higher stress levels.

$$F = C + \alpha(\sigma_x+\sigma_y)/2 - \{(\sigma_x-\sigma_y)/2 + (\sigma_{xy})^2\}^{½} \quad .... \; 3.15$$

where:

F = the stress at yield point (Pa),

C = the vertical intercept on the q-axis in the p-q space,

α = the slope of the failure surface,

σ_x = direct stress applied in the x-direction (Pa),

σ_y = direct stress applied in the y-direction (Pa), and

σ_{xy} = the stress applied in the xy-direction (Pa).

3.3. The Interaction Between Soil and the Running Gear

In a study of the effects of dynamic load on thrust components along the soil-tyre contact zone (Wood et al., 1989) observed that the tyre developed

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thrust more uniformly across the lug face in loose than in compacted soil conditions.

Salokhe et al. (1989) measured lug forces on a single model cage wheel lug in wet clay soil. They found that increase in lug sinkage showed almost proportionate increase in lug forces while increase in soil moisture showed decrease in lug forces. In addition they noticed that lug angle, lug width, lug shape and travel reduction had a strong effect on lug forces. Further, the measured lug forces were found to be in reasonable agreement with the forces predicted by using the conventional passive pressure theory in a two dimensional perspective, (see Equation 3.16).

$$P = \tau Z^2 N\tau + CZNc + CaZNa + qZNq \qquad \ldots\ldots\ 3.16$$

where:

P = force created on the device (kN),

τ = specific weight in kN/m,

Z = sinkage in m,

C = soil-metal cohesion in kPa,

Ca = soil-metal adhesion in kPa, and

$N\tau$, Nc, Na and Nq are dimensionless constants.

The explanation offered for the observation by Salokhe et al. (1989) was that at the time of lug entry, soil failed vertically due to the initial compression caused by the downward movement of the lug. The soil just below the lug offered a severe resistance to this compression. Due to the compression, normal lug force increased continuously until it attained a peak value. After a few degrees of initial lug rotation the vertical failure changed into a horizontal failure. Due to this, further lug rotation caused a horizontal pushing of soil in front of the lug and the soil flowed above the horizontal soil surface where it experienced the least resistance to deformation.

Overall, a good understanding of how the forces act on the running gear enables one to predict the magnitude and type of forces whenever there is need for design. More consideration on soil compaction may be made with such knowledge.

3.4. Effects of Soil Properties on Force-Compaction Relationships

3.4.1. Effect of Type of Soil

In tests conducted by Vanden Berg (1958) the relationships determined between mean stress and bulk density were influenced by soil type. Typical curves from Decatur silt clay loam and Llyod clay with moisture contents of 16 and 19% respectively showed that both the rate of change and total change in bulk density were greater for silt loam than for the clay, within the range of mean stress conditions. Similar data for a sandy loam soil with an average moisture content of 9% indicated a rate of change in bulk density slightly higher than of the silt clay loam.

Hovanesian (1958) noted that soil type affects the relationship between mean stress and bulk density. Bekker (1957) also noted that the parameters in equation 3.8 depended on the type of soil. These parameters were higher for loam than sandy loam soil when compared at the same moisture content. Soehne (1958) found that the slope in equation 3.4 varied with soil type. Values of A were about 10, 14 and 12 for sand, loam and loam clay respectively. For a given pressure increase, the porosity of the clay decreased more than the other soil types, while the smallest decrease occurred in the sandy soil.

3.4.2. Effect of Particle-Size Distribution

Particle-size distribution influences the chemical, physical, and biological properties of soils. Larger particles of sand and gravel form the skeleton of the soil and determine many of its mechanical properties. The fine particles of clay have large surface areas per unit volume and they determine most of the chemical and physical-chemical properties of soils.

Particle-size distribution has an influence on strength, compressibility, water movement, temperature and aeration in soils. A change in void ratio with compaction is greater for a poorly graded soil than for a well-graded soil. A well graded soil contains both coarse- and fine-grained particles. In this soil the number of particle contacts and the areas of contact for any one particle will be greater than in poorly graded soil. Resistance to shear-induced motion will therefore be greater and the change in void ratio for any single load application will be less than would occur with a poorly graded soil. In fine-grained soils where the pore size is smaller than in coarse-grained material the effect of capillarity will be greater and the amount of moisture present should be greater than in coarse-grained soils.

3.4.3. Effect of Type of Clay Mineral

Two clay soils with the same particle-size distribution can have very different colloidal properties, depending upon the mineral type. Clay particles are always surrounded by layers of water molecules called adsorbed water. Plasticity, compaction, interparticle bonding, and water movement in soils are all related to the water layers. Each successive layer is held less strongly and the bonding quickly decreases to that of free water. The properties of the water close to the clay are different from those of free water.

Density is higher for the layer of water molecules close to the soil particle and it decreases outwards from the particle. The viscosity of the water layer close to the soil particle may be a hundred times greater than that of free water. The amount of swelling depends on the clay minerals and their arrangement or orientation. The swelling also depends on exchangeable cations, pore-water salt concentration, and cementing bonds between clay particles.

Transition soils (fine sand, rock flour, silt) are soils with characteristics between sand and clay soils. When these soils are compacted at increasing moisture content, soil strength increases up to a maximum at the optimum moisture content then it decreases. This can be attributed to the following. The bonds between the particles are weak, and are therefore very sensitive to any variation of water content. A small percent change may lead to the complete loss of strength. This loss in strength as more water is added makes the compaction of the soil increase because the resistance offered by the soil particles to the compacting force is reduced (Kezdi, 1979).

If macro-pores (sphere-like pores which are much greater than the grains) are present, then the compression of the sample at static load will be slight (Kezdi, 1979). However, with water added a sudden collapse occurs. Increase in the amount of water in the soil perhaps leads to more collapse of the grains enabling the soil compaction to increase as well.

When the soil is relatively dry, during compaction no change in the moisture content occurs. The soil is far from being saturated and the deformation is inelastic. As moisture content increases to the vicinity of the optimum value the soil becomes highly elastic such that an increase on load may compact the soil, but on removal of the load the particles rebound to their original positions.

When the moisture content is increased beyond the optimum, compaction is achieved only if water is squeezed out. In a Proctor test the soil is confined such that moisture does not escape easily. The response of soil to an applied load is merely a displacement one. This reduces the amount of soil per given volume in the compaction mould. The position of the limit line depends on the mutual effects of the solid-water system on the physical properties of the grain surface and on the grain size distribution curve. Compaction leads to a decrease in both void ratio and pore water.

3.4.4. Effect of Soil Moisture Content

Moisture is almost always present in the soil mass and it influences the behaviour of the soil in response to external forces. Coarse-textured soils exhibit high capillary potential at low moisture contents. Finer textured soils hold a greater quantity of water at the same potential because of the greater number of contacts. There is an optimum moisture at which maximum compaction occurs for a given amount of energy applied during the compaction process. In general, for partly saturated conditions, the higher the moisture content of the soil, the more it is compacted by a given pressure. After reaching the saturation point, changes in compaction would result only by squeezing water out of the sample.

Data obtained by Hovanesian (1958) in developing equation 3.17 presented below, indicated that both soil type and soil moisture must be considered in using the relationship to predict changes in bulk density when a mass of soil is subjected to a given condition of mean stress.

$$p_b = p_0 + B \ln((p_m/p_0+c)/(1+c)) \qquad \ldots\ldots 3.17$$

where:

P_b = bulk density (g/cc),

p_0 = initial bulk density under initial load condition P_0 (g/cc),

p_m = mean stress (Pa), and

c, B = parameters that depend on soil properties.

In studies of hardpan formation (Gerard et al., 1964), it was found that the most important factor influencing compaction in soils under cultivation was the moisture content during the tillage operations. Coarse-textured soils were extremely susceptible to compaction when tilled at high moisture contents. Hegedus (1958) reported that very slight changes in moisture content modify the magnitude of the parameters in equation 3.7. In general, the three parameters in the equation decrease as the moisture content of the soil increases.

3.4.5. Effect of Bulk Density

Although the state of compaction can be completely specified by giving the bulk density, the usual definition of the weight of oven-dry soil per unit of the bulk volume is the most difficult to use to predict behaviour of a soil subjected to an applied load. The bulk density can be related to porosity and void ratio, (Equations 3.18 and 3.19).

$$n = 1 - p_b/p_s \quad \text{.... 3.18}$$

$$n = e/(1+e) \quad \text{.... 3.19}$$

where:

n = porosity defined as the ratio of the volume of pore spaces or voids to the total volume,

e = void ratio defined as ratio between void volume and volume of solids,

p_b = dry bulk density (g/cc), and

p_s = unit weights of the solid (g/cc).

At a given moisture content, an increase in initial bulk density increases values of k_c and k_ϕ in equation 3.8. In general, for a given soil subjected to a set of external forces, the lower the initial bulk density, the greater the volume change. This is particularly true if the structure of the soil has been affected by tillage operations.

4. MATERIALS AND METHODS

4.1. Soil Sampling Process

An easily assembled core sampler was locally fabricated as described by Wells (1959) and is shown in Figure 4.1. The samples were used to determine soil bulk density and moisture content values. Other alternative equipment like the piston-type, single tube barrel and double tube barrel soil samplers were not available.

The sampling equipment consisted of a sampling tube of 52 mm internal diameter and 100 mm depth in which two core rings were placed. Each of the 100 cm^3 core rings measured 49.0 mm internal diameter and 52.5 mm high. To provide least distortion to the samples, the cutting edge of the sampling tube was chamfered from the outside, the inside of the cylinder was relieved above the cutting edge, the walls were thin and the sampler head was not allowed contact with the soil surface. Hammering however caused some starts and stops that might have fractured the soil core.

When sampling soil, it was expected that the upper core ring received least disturbances, therefore it is the one that should be taken for bulk density analysis. However, in this experiment it was not possible to fill the upper core ring with enough soil even after letting the whole depth of the sampling tube into the soil. In effect soil in the lower core ring was the one used for bulk density measurement.

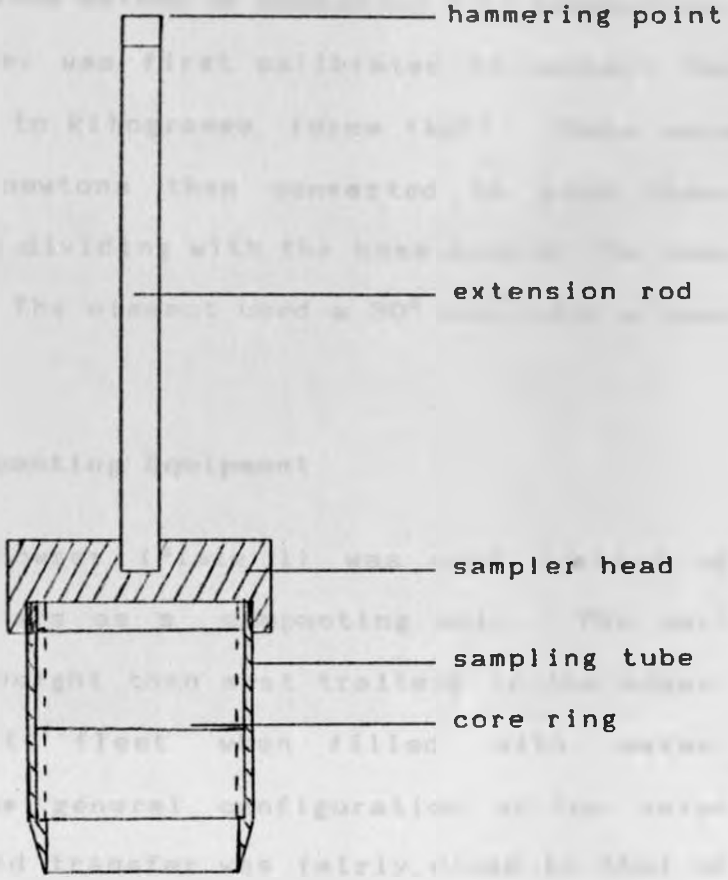


Fig. 4.1 Core soil sampler.

4.2. Measurement of Soil Bearing Capacity

Barnes et al. (1971) reported that penetration tests have long been used in studying soil properties and their relations to stresses imposed by external agencies. However, the results of penetration tests are affected by the size, shape, and surface textures of the penetrating element, the rate and manner in which the element is advanced and the method of interpreting the results.

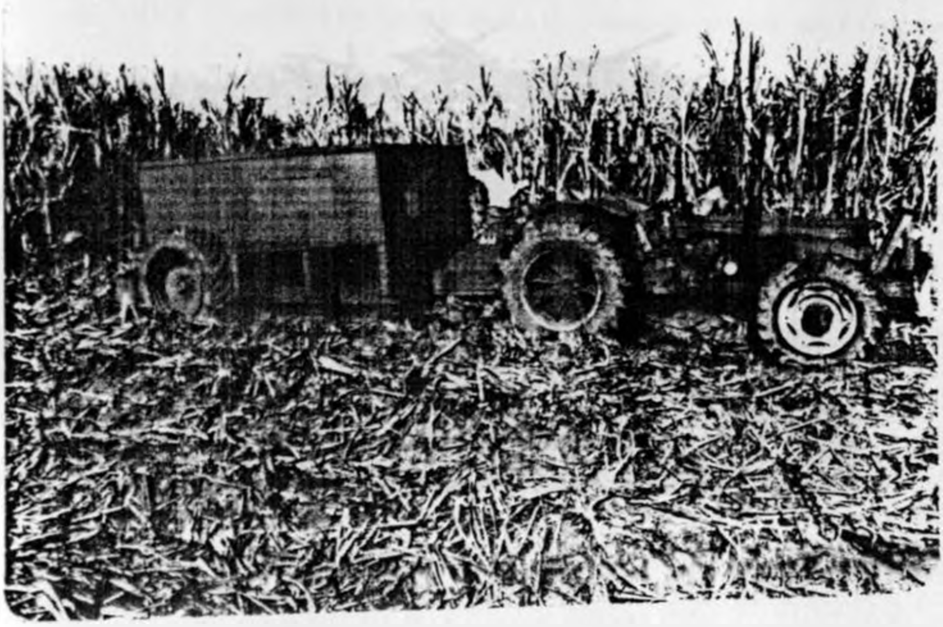
In this study, penetrometer tests provide a quick and less laborious method of measuring soil compaction. The penetrometer was first calibrated to convert the scale readings to kilogramme force (kgf). These were changed into newtons then converted to cone index values (kPa) by dividing with the base area of the cone element used. The element used a 30^0 cone with a base area of 95 mm^2.

4.3. Soil Compacting Equipment

A Water Bowser (Plate 1) was used instead of sugarcane trailers as a compacting unit. The unit carried more weight than most trailers in the sugarcane transport fleet when filled with water. Apart from the general configuration of the water bowser, its load transfer was fairly close to that of both the single bundle and the nucleus estate trailers (see Plates 2 and 3).

The weight of the vehicle (tractor and bowser) on the weigh-bridge was 6400 kg. The bowser axle load was 2590 kg. The weight of the tractor alone was 2810 kg. The weight of the empty bowser was therefore 3590 kg When empty the bowser transferred 1000 kg to the tractor. This was slightly less than the load transferred to the tractor by either a single bundle trailer or a box type (nucleus estate) trailer of 1560 and 1600 kg respectively.

To increase the axle loading of the bowser, an



The presence of trash in the field may be reduced the induced soil compaction by traffic.

Plate 1. Water Bowser.

extra 2.3 tonnes of a metal load was added into it. The axle loads could easily be varied by letting out some water. This made room for the easy control of axle loads applied to the soil. The water bowser was calibrated before it was used (see Appendix 3). During the test one merely made a water level reading and with the help of calibration results the corresponding axle load was determined.

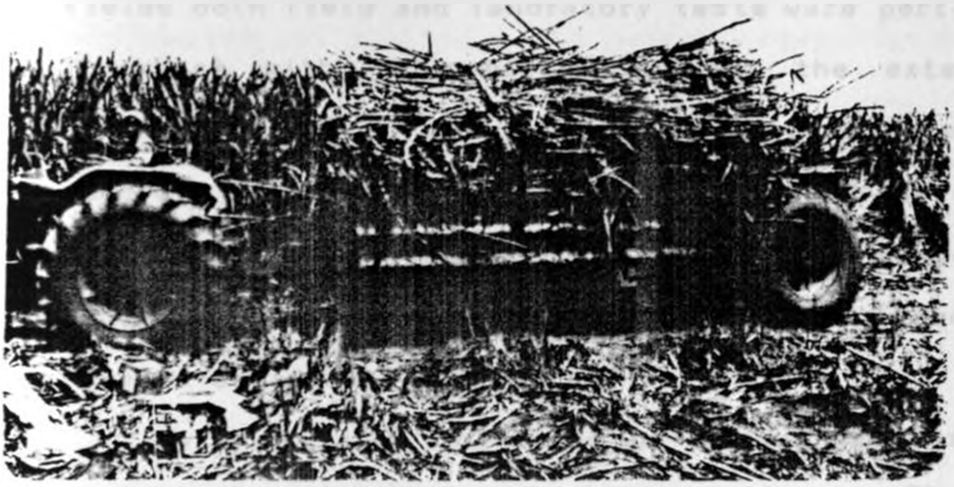


Plate 2. Single Bundle Trailer.

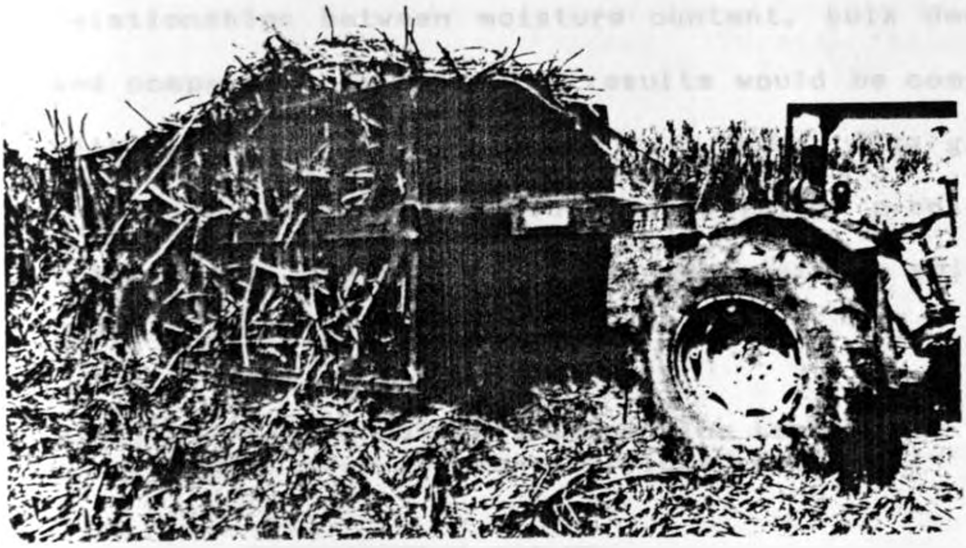


Plate 3. Nucleus Estate Trailer.

4.4. Soil Compaction Studies

To complete a study on compaction effects of transport vehicles on Mumias Sugar Company sugarcane fields both field and laboratory tests were performed. To start with, investigations into the extent of compaction due to previous field traffic were conducted. These were followed by field tests to establish safe axle loads beyond which the compaction induced by various transport vehicles would be considered detrimental to the soil.

Data was then collected on loaded trailer axle loads and payloads for various trailers. The data collected was used to select trailer units that would be unlikely to cause detrimental soil compaction based on the established safe axle loads and ground contact pressures.

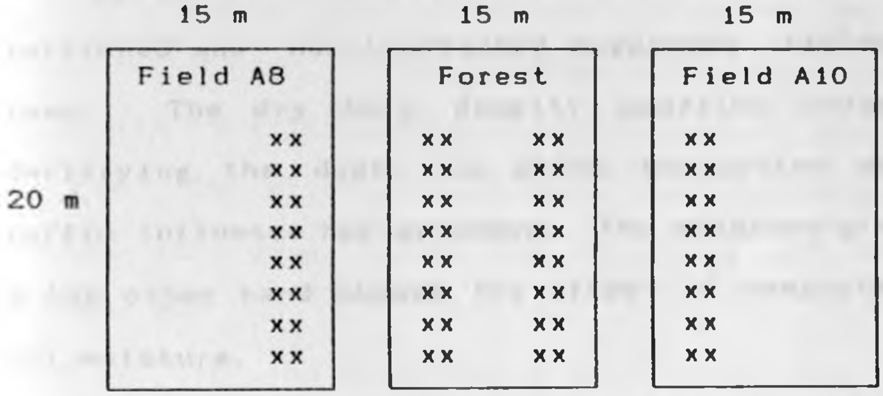
Laboratory test were conducted to establish the relationships between moisture content, bulk density and compaction effort. The results would be compared with the ones obtained from field tests. The graphs for these relationships would be useful in predicting induced soil compaction levels under various soil and effort conditions.

4.4.1. Comparison of Soil Compaction Levels in Trafficked and Non-Trafficked Fields

4.4.1.1. Experimental Set Up

The bulk density comparisons were conducted at

Mumias in the Nucleus Estate sugarcane fields A8, A10 and a forest adjacent to them. Figure 4.2 shows the experimental set up. Textural and organic matter analysis were conducted on the soil using the standard hydrometer and Walkley-Black methods respectively. The research sites were two extensively trafficked fields and one non-trafficked field. Each site measured 15x20 m.



x: samples for dry bulk density determination taken from here.

Figure 4.2. Sites for trafficked (A8 and A10) and non-trafficked (Forest) fields.

4.4.1.2. Procedure and Analysis

Samples for bulk density were taken from a depth of 10 cm up to 50 cm in steps of 10 cm using the core soil sampler shown in Figure 4.1. A total of 48 and 32 soil samples were taken at random on the surface and in the subsoil (respectively) at each site. Soil was trimmed flat, using a sharp knife, at the top and bottom ends of the desired core ring to maintain a volume of 100 cm^3. The samples were weighed before and after oven drying at 105°C for two days. Dry bulk density was calculated by dividing the dry weight of the soil by the inside volume of the core ring. The moisture content was calculated by dividing the weight of the water after oven drying by the wet weight of the soil.

Graphs showing the profiles of dry bulk density and gravimetric water content for extensively trafficked and non-trafficked sugarcane fields were drawn. The dry bulk density profiles helped in identifying the depth to which compaction due to traffic influence had extended. The moisture profiles on the other hand showed the effect of compaction on soil moisture.

A statistical analysis using a t-test based on the principle of comparison of two independent samples with an equal variance at 5 percent confidence level (Steel and Torrie, 1987) was performed. This test compared mean dry bulk density values in trafficked and non-trafficked fields, first on the surface layer (0 to 30 cm) and next in the subsoil layer (30 to 50 cm).

The influence of soil moisture content on soil dry bulk density was also statistically analyzed. The influence of soil type on dry bulk density was determined. To decide on whether soil type affected the measured dry bulk density values, a comparison of the various proportions of sand, silt and clay for the different soils tested was made. In case the type of soil affected the measured dry bulk density, variation in the proportions of say sand for one of the soil types would be followed by variation in dry bulk density values.

4.4.2. Establishment of Safe Axle Loads

4.4.2.1. Experimental Set Up

Following the preliminary studies at Mumias reported above, field studies were established in February 1990 at three different sites in the Nucleus Estate. The sites were selected on the basis of crop stage, bulk density and type of soil. All the three fields had on them sugarcane ready for harvesting. Fields A18x and D118x had a plant crop, and field B3 had a first ratoon crop. Sugarcane was harvested and carried out of the fields by hand labour. The trash, however, was carried out with the help of a 3.5 tonne bell loader running on 18.4x30 tyres with an inflation pressure of 104 kPa. This unit was chosen because its soil compaction effects compared with that from sugarcane transport vehicles were considered negligible.

At each site three levels of moisture content and inflation pressure and four levels of axle load of soil compaction were utilized in a split-split plot design as shown in Figure 4.3. The detailed experimental layout is shown in Appendix 4.

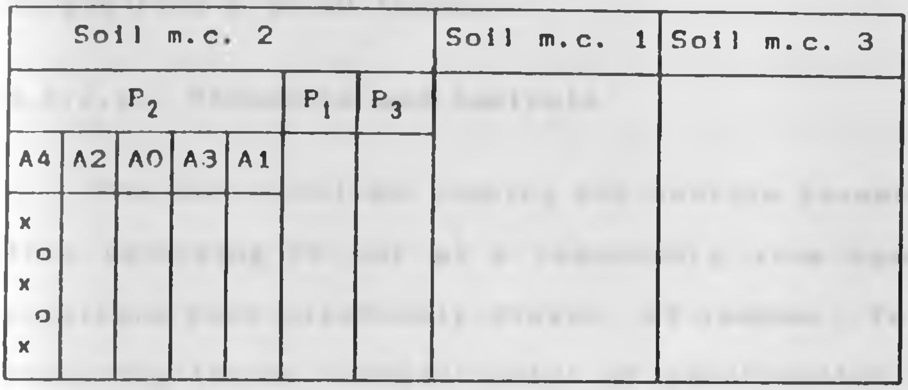


Figure 4.3. A schematic diagram of the experimental layout.

This is a split-split plot design in which each site is a block, each moisture is a main plot, each tyre inflation pressure is a subplot and each axle loading is a sub-subplot. Here P_1 to P_3 are different trailer tyre inflation pressures, A0 to A4 are different axle loads applied, and x and o are the points in which samples for bulk density and penetrometer readings were taken (respectively).

The control treatment involved no compaction except from that caused by previous field operations. The highest moisture content obtained in all the three fields was after heavy rains. Lower moisture contents were achieved by letting the fields dry naturally. A water bowser was used for the compaction treatments. The experiments were designed in such a way that on any particular day a set of treatments had to be completed lest the weather conditions varied. Tyre inflation pressures used were 180, 207 and 235 kPa depending on the treatment required. The tractor tyre inflation pressures were 152 and 180 kPa for the front and rear respectively, and the water bowser axle loads used ranged from 5 to 10 tonnes.

4.4.2.2. Procedure and Analysis

The test involved running the vehicle forward and then reversing it out at a reasonably slow speed in sugarcane rows previously chosen at random. Two and three replicates (respectively) of penetrometer readings and soil samples for bulk density analysis were taken. The cone readings were taken to a depth of 40 cm in steps of 8 cm starting at the soil surface. Samples for bulk density were taken using the soil sampler shown in Figure 4.1 and described in Section 4.1. The samples were taken at depths of 10 and 20 cm. Further depths of 30 and 40 cm were used for samples in the 9 tonnes and control treatments. These would be used in showing the variation of soil compaction with depth.

An estimate of tyre contact area was obtained from equation 4.1. This equation shows the relationship between the area of contact and the largest dimensions of an ellipse.

$$\text{Area of contact} = 0.886 \times LW \qquad \ldots. \ 4.1$$

where:

L, W = the largest length and width of the ellipse respectively (m).

The elliptical patches were obtained by sprinkling a white powder around the edge of the contact area. The vehicle was then driven off, and a sheet of clear plastic (polythene) was placed on the soil. The contact area, clearly outlined by the white powder, was then drawn with felt pen. The contact area was later measured from the plastic sheet by counting the squares covered. The largest length and width were measured for all the ellipses formed. A regression analysis was performed on some randomly chosen ellipses traced out of the area of contact to develop this relationship, (see Appendix 5).

To analyze the data, graphs showing the following relationships were developed:

(i) mean dry bulk densities against loaded trailer axle loads for various levels of soil moisture content, inflation pressure and different soil types,

(ii) ground contact pressures against loaded trailer axle loads and

(iii) mean cone index values against ground contact pressures for various levels of soil moisture content, inflation pressure and different soil types.

Two types of curves were considered to best describe the data. These were a power curve (Equation 4.2) and an exponential curve (Equation 4.3). Using curvilinear analysis, Little et al. (1978), empirical equations based on these two curves were determined. The equations related induced soil compaction and the compacting effort. Possible explanations for the graphical observations were offered.

$$Y = aX^{b} \qquad \ldots\ldots\ 4.2$$

$$Y = ab^{kx} \qquad \ldots\ldots\ 4.3$$

where:

Y = resulting compaction (g/cc),

X,x = compacting effort (kN) and

a, b, k = are constants which depend on soil properties.

Two approaches were used to establish the safe trailer axle loads. These were:

(i) the safe trailer axle loads were computed on the basis of a critical bulk density value chosen from Table 2.2.

(ii) the safe trailer axle loads were established from a statistical analysis. Here the significance difference of induced soil compaction due to various compaction efforts from the compaction in non-treated sections were determined.

Using the critical bulk density approach the safe trailer axle load was computed directly from the relationship between dry bulk density and the applied trailer axle load. To avoid extrapolation, graphs whose maximum induced soil compaction values exceeded or were close to the critical soil bulk density value were the only ones considered for the computation of safe trailer axle loads.

The statistical approach on the other hand compared the induced soil compaction levels for the various compaction pressures with soil compaction in sections where no load was applied. The analysis used t-tests based on the principle of comparison of two independent samples with an equal variance at 5 percent confidence level (Steel and Torrie, 1987). A safe ground contact pressure beyond which compaction was considered significant was established. Using this safe ground contact pressure and relationships between ground contact pressures and trailer axle loads, safe axle loads were computed.

It was important to choose one of these two methods (that is the critical bulk density and the statistical methods) based on the one which gave reasonable safe trailer axle loads. In order to make this choice tyre specification manuals for an agricultural environment were used. In these manuals tables for the permissible trailer axle loads for various tyre sizes and inflation pressures are given. The method whose computed safe trailer axle loads at the various inflation pressures was close to the values in the tables was selected as the better of the two. The safe trailer axle load obtained using this method was then used in the analysis of suitable trailers units.

4.4.3. Analysis of Suitable Trailer Units

4.4.3.1. Experimental Set Up

Data to be used to select trailer units that would be unlikely to cause detrimental soil compaction was collected at the weigh-bridges of Mumias between February and April, 1990. Two types of trailers were utilized: single bundle trailer (SBT) and box type or nucleus estate trailer (NET), (see Plates 2 and 3). A small amount of data was gathered for a High Capacity Bin Trailer (HCBT, Plate 4) due to its low availability. Five types of prime movers were used to pull

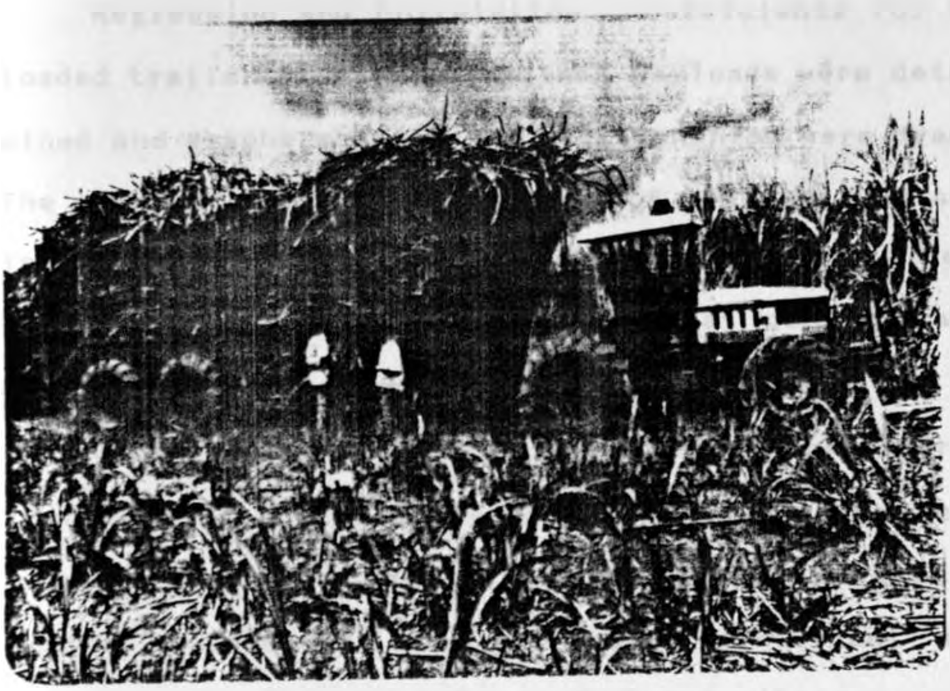


Plate 4. High Capacity Bin Trailer.

both the SBT and NET. These were: John Deere 2250, 2WD; Same Explorer 80, 4WD; Same Centauro 75, 4WD; Same Saturno 80, 2WD and Ford 5610, 2WD tractors. The HCBT was pulled by either a Deutz-Fahr tractor or a 4WD Lamborghini 956.

4.4.3.2. Procedure and Analysis

Data collection involved recording weigh-bridge readings when the:

(i) loaded vehicle was on the weigh-bridge,
(ii) loaded trailer was alone on the weigh-bridge,
(iii)empty vehicle was on the weigh-bridge and,
(iv) empty trailer was on the weigh-bridge.

Regression and correlation coefficients for the loaded trailer axle loads against payloads were determined and graphs showing the relationships were drawn. The mean and standard deviations of payloads and axle loads, when the trailers were loaded were determined.

To select the trailer units that do not cause detrimental soil compaction, the proportion of the number of trailers, for each trailer type, that carried in excess of the established safe axle load was computed. Where the proportion was zero the type of trailer considered did not cause significant soil compaction. Otherwise some of the trailers caused significant soil compaction.

Safe payloads were determined from the established relationships between loaded trailer axle loads and payloads. Where the safe payloads fell above the sum of mean payload and the corresponding standard deviation, it was recommended that the amount of sugarcane carried by this type of trailers should be increased to the maximum possible payload to get maximum profits.

4.4.4. The Proctor Test Analysis

It was necessary to conduct laboratory tests to determine the relationships between soil moisture, bulk density and the compaction effort. These would be used to predict compaction levels for a wide range of soil moisture and load conditions. The moisture range available during the field tests was very narrow, therefore there was need to look for an alternative method which would widen this range. There was also need to find out if maximum compaction had been attained with the narrow field moisture range used. A comparison of the results of the Proctor test and field treatments would be useful in the prediction of compaction due to machinery in the fields knowing field and loading conditions.

The response of soils in the fields to compaction pressures was greatly affected by such factors as variability in soil structure, soil strength, distribution of soil moisture and organic matter. Only under laboratory conditions was it possible to have uniformity in soil strength, soil structure and soil moisture by thoroughly mixing the soil.

4.4.4.1. Experimental Set Up

To compare field and laboratory results, it was desired that a sampler as described by Foale and Upchurch (1982) be used to get undisturbed soil samples to depths of about 40 cm. This equipment was not available. The samples would be subjected to pressures similar to ground contact pressures developed by sugarcane transport trailers. The degree of soil compaction at various depths would then be investigated by measuring soil bulk densities at different points along the sample depth.

The Proctor Test, Appendix 6 (Bowles, 1978), with modifications provided an alternative suitable approach for the comparison between field and laboratory results. Instead of using an impact force as used in Proctor Tests, a compression force was applied. This simulated pressures that are normally exerted to the soil by field vehicles. A self-fabricated compaction mould and a compacting unit attached to a penetrometer (see Fig.4.4) were used to generate these pressures.

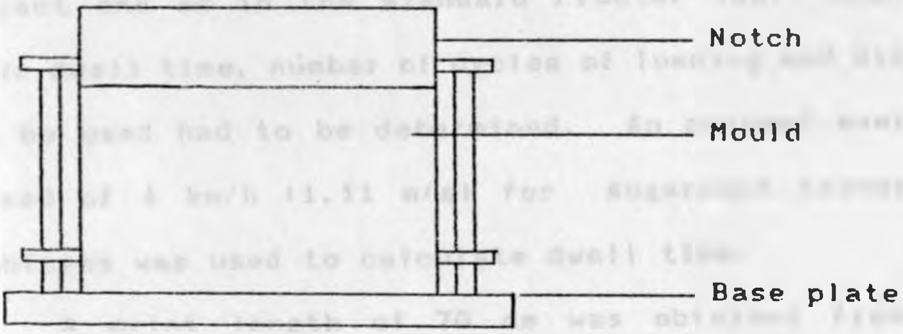


Fig. 4.4. Apparatus used in the Proctor test.

The dimensions of the mould were as per the requirements of the standard Proctor Test. The penetrometer was used because it provided the scale on which to read directly the pressure being applied.

4.4.4.2. Procedure and Analysis

The test to determine the relationships between soil moisture content, dry bulk density and compaction effort were conducted in the Agronomy Section Laboratory of Mumias Sugar Company. Soil was sampled from the three experimental sites of Section 4.4.2 from both surface and subsoil layers. The soils from the two layers were mixed for each field. The soils were then sun-dried for three days and crushed to pass through Number Four sieve. Eight levels of moisture content in increments of 2% from 6 to 24% (wet weight) were used. In order to use compaction pressures close to the values caused by the compaction vehicles used in the field, stress values of 108, 142, 151 and 169 kPa were applied.

Since the load applied was compressive (and not an impact one as in the standard Proctor Test) aspects like dwell time, number of cycles of loading and stress to be used had to be determined. An assumed average speed of 4 km/h (1.11 m/s) for sugarcane transport vehicles was used to calculate dwell time.

A print length of 70 cm was obtained from an 18.4x30 tyre. Dwell time was 0.63 seconds per pass.

For four passes dwell time was 2.52 seconds. This was approximated by a 3.0 second duration. Four passes were achieved out of the 18.4x30 tyres on the vehicle during the field tests. The assumption was that the sum of ground contact pressures developed by the tractor rear and front tyres was equal to that developed by the water bowser tyre. This is supported by the calculation shown in Appendix 7.

The number of cycles of loading per layer was obtained by dividing the area of the mould by that of the compacting unit.

The results were first used to plot graphs of dry bulk density against moisture content at various load applications for the different soil types. A comparison of the Proctor and field tests results for the same soil type, compaction pressure and moisture content was made. The moisture content at which maximum compaction occurred was determined. This gave an indication of the moisture conditions under which the soils of Mumias Sugar Company are most vulnerable to compaction.

5. RESULTS AND ANALYSIS

To accomplish objectives of the research study on the effects of soil compaction on the sugarcane fields of Mumias Sugar Company it was necessary to make careful observations during the field tests.

5.1. The Types of Soil in Trafficked and Non-Trafficked Fields

A textural analysis for the soils at the three experimental sites was done (see Tables 5.1 and 5.2). Table 5.1 shows that the three sites had different soil types in the soil surface with no difference in the subsoil. The differences in the proportions of sand, silt and clay for the soils of fields A8 and F were only 5.6, 3 and 2.6 percent (Table 5.2) respectively. Similarly the differences in proportions of sand and clay for field sites A8 and A10 were as high as 17.4 and 21.4 percent (respectively).

Table 5.1. Types of soil in trafficked (A8 and A10) and non-trafficked (F) fields.

Field	surface	subsoil
A8	sandy clay loam	sandy clay loam
A10	loam	sandy clay loam
F	sandy loam	sandy clay loam

Table 5.2. Soil texture in trafficked (A8 and A10) and non-trafficked (F) fields.

	Texture (%)					
	surface (0-30) cm			subsoil (30-50) cm		
Field	sand	clay	silt	sand	clay	silt
A8	64.8	21.2	14.0	69.9	24.7	5.40
A10	47.4	17.2	35.4	66.4	30.2	3.40
F	70.4	18.2	11.4	72.2	24.4	3.20

5.2. Dry Bulk Density and Moisture Distribution

In order to confirm that infield traffic causes significant soil compaction, the levels of soil compaction between sugarcane fields with and without infield use of transport vehicles were measured. Samples for this study were taken from fields A8 and A10 (fields with traffic influence) and F (field without traffic influence). Profiles of dry bulk density and gravimetric water content in the field sites at the time of sampling are shown in Figures 5.1 and 5.2.

Comparison of graphs A8 and A10 with F (Figure 5.1 and Table 5.3) shows that the fields with traffic influence had higher dry bulk density values which were significant at 5 percent confidence level in the layer between 0 and 30 cm soil depth than those without traffic influence. The difference was insignificant for the soil layer between 30 and 50 cm for trafficked and non-trafficked fields. The mean dry bulk density in the soil layer 0 to 30 cm for fields without traffic influence was 1.35 g/cm^3.

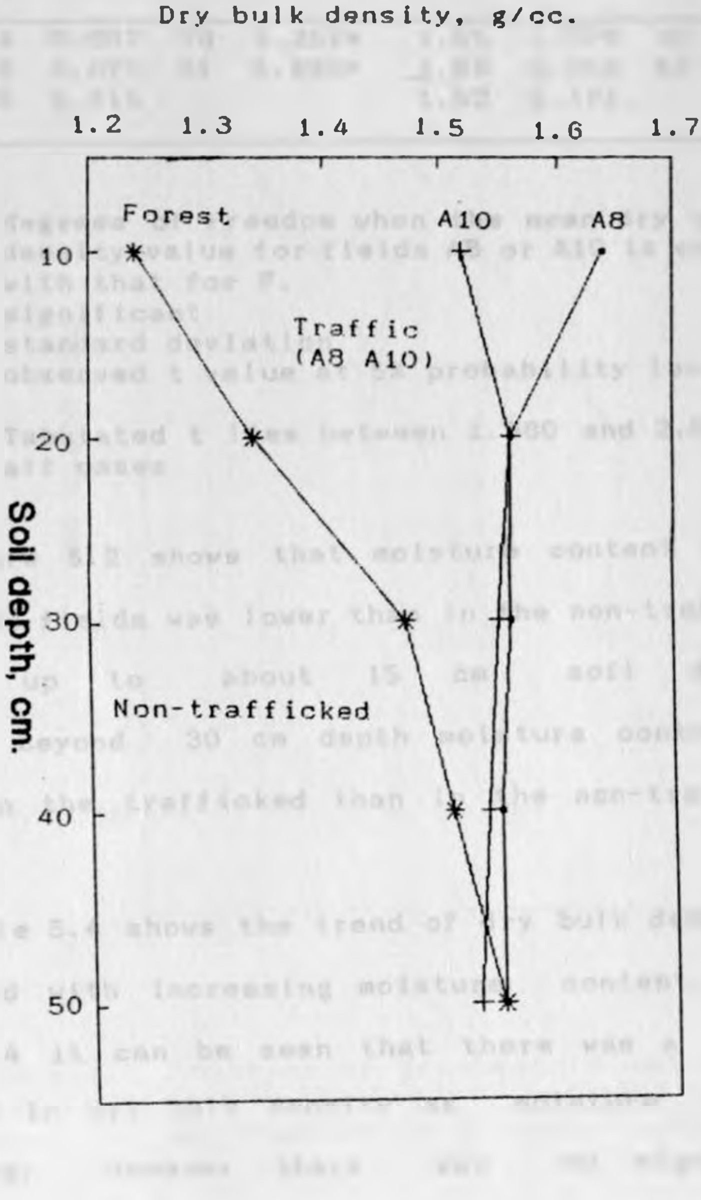


Figure 5.1. Profiles of bulk density for trafficked and non-trafficked fields.

Table 5.3. Mean dry bulk densities (g/cm^3) for trafficked (A8, A10) and non-trafficked (F) fields.

	Surface (0-30) cm				Subsoil (30-50) cm			
Field	mean	s.d	df	t	mean	s.d	df	t
A8	1.59	0.087	70	5.254*	1.55	0.078	46	0.235
A10	1.55	0.076	94	5.969*	1.54	0.054	63	0.272
F	1.35	0.215			1.52	0.191		

df = degrees of freedom when the mean dry bulk density value for fields A8 or A10 is compared with that for F.
* = significant
s.d = standard deviation
t = observed t value at 5% probability level.

Tabulated t lies between 1.980 and 2.021 in all cases

Figure 5.2 shows that moisture content in the trafficked fields was lower than in the non-trafficked fields, up to about 15 cm soil depth. However, beyond 30 cm depth moisture content was higher in the trafficked than in the non-trafficked fields.

Table 5.4 shows the trend of dry bulk density as it varied with increasing moisture content. From Table 5.4 it can be seen that there was a general decrease in dry bulk density as moisture content increased. However there was no significant difference in moisture content in the three fields. It is also noticeable that the differences in mean moisture content between fields A8 and A10, and A8 and F were similar while the corresponding differences in

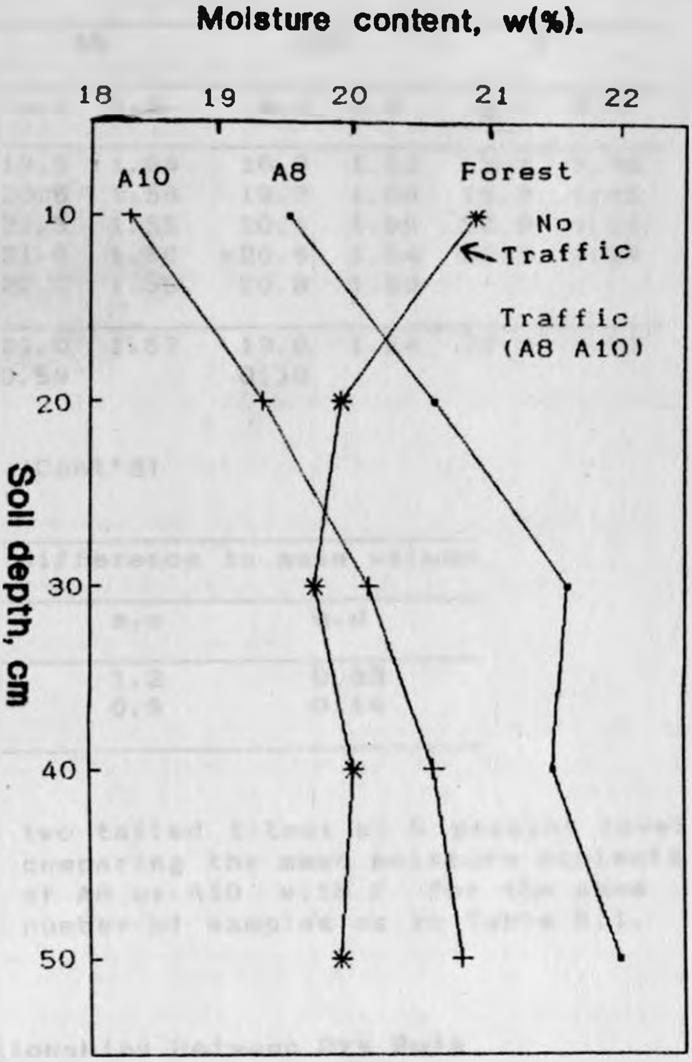


Figure 5.2. Profiles of gravimetric water content for trafficked (A8 and A10) and non-trafficked (Forest) fields.

mean dry bulk density values were not.

Table 5.4. Dry bulk density variation with increasing moisture content

Field	A8		A10		F	
	m.c	b.d	m.c	b.d	m.c	b.d
	19.5	1.64	18.3	1.52	19.7	1.46
	20.6	1.56	19.3	1.56	19.9	1.45
	21.5	1.55	20.1	1.55	20.0	1.55
	21.6	1.56	20.6	1.54	20.9	1.24
	22.0	1.55	20.8	1.53		
mean	21.0	1.57	19.8	1.54	20.1	1.43
t(p=0.05)	0.59		0.18			

Table 5.4. (Cont'd)

	difference in mean values	
Field	m.c	b.d
A8 and A10	1.2	0.03
A8 and F	0.9	0.14

t(p=0.05) = two-tailed t-test at 5 percent level comparing the mean moisture contents of A8 or A10 with F for the same number of samples as in Table 5.1.

5.2. Relationships Between Dry Bulk Density and Applied Load

Tables 5.5a to 5.5c show dry bulk density values as affected by the applied load. The dry bulk density data for each tyre pressure row is related to the applied load by Equation 5.1. A curvilinear analysis as described by Little and Hills (1978) was performed to determine the constants a and b in Equation 5.1, and the corresponding correlation coefficient. The results are also shown in Tables 5.5a to 5.5c.

$$p_d = a\ e^{bL} \qquad \text{.....} \ 5.1$$

where:

a, b = soil constants,

p_d = mean dry bulk density (g/cm^3), and

L = load per tyre, kN.

Figures 5.3 and 5.4 are based on the data from Tables 5.5a and 5.5b. They show the effect of the applied load per tyre on mean dry bulk density at sites A18x and B3 respectively. The figures show that in general there was an increase in mean dry bulk density with increased load application for moisture contents not greater than 22 percent (wet weight).

Table 5.5a. Soil dry bulk density (at 10 cm soil depth) as affected by applied load per tyre (L) at site A18x for various moisture and tyre pressures

L (kN)		26.0	34.4	39.3	44.2			
A	B	Bulk density (g/cc)				a	b	r^2
180		1.487	1.493	1.507	1.520	1.438	0.0012	0.914
207	17.2	1.507	1.517	1.528	1.568	1.423	0.0020	0.802
235		1.567	1.584	1.590	1.600	1.522	0.0011	0.995
180		1.520	1.553	1.560	1.590	1.430	0.0024	0.965
207	21.3	1.527	1.550	1.577	1.613	1.408	0.0030	0.950
235		1.480	1.524	1.520	1.571	1.370	0.0030	0.881
180	22.1	1.368	1.426	1.373	1.340	1.439	-0.0012	0.137
207		1.467	1.409	1.493	1.373	1.559	-0.0023	0.220

Table 5.5b. Soil dry bulk density (at 10 cm soil depth) as affected by applied load per tyre (L) at site B3 for various moisture contents and tyre pressures

L (kN)		26.0	34.4	39.3	45.2			
A	B	Bulk density (g/cc)				a	b	r^2
180		1.474	1.493	1.496	1.513	1.425	0.0013	0.968
207	18.3	1.514	1.512	1.519	1.524	1.497	0.0004	0.690
235		1.508	1.542	1.582	1.602	1.389	0.0031	0.984
180		1.487	1.494	1.513	1.570	1.375	0.0027	0.790
207	20.8	1.463	1.487	1.524	1.587	1.302	0.0042	0.918
235		1.487	1.491	1.487	1.554	1.400	0.0020	0.551
180		1.429	1.433	1.501	1.504	1.313	0.0031	0.777
207	20.9	1.482	1.535	1.508	1.512	1.463	0.0009	0.233
235		1.509	1.507	1.516	1.516	1.496	0.0003	0.593

Table 5.5c. Soil dry bulk density (at 10 cm soil depth) as affected by applied load per tyre (L) at site D118x for various moisture contents and tyre pressures

L (kN)		26.0	34.4	39.3	45.2			
A	B	Bulk density (g/cc)				a	b	r^2
207	22.4	1.258	1.314	1.362	1.259	1.257	0.0009	0.034
		1.341	1.320	1.474	1.301	1.346	0.0002	0.001
235	24.4	1.578	1.286	1.276	1.213	2.159	-0.0130	0.869
		1.259	1.251	1.283	1.317	1.171	0.0024	0.710

a, b = constants in ($p_d = ae^{bL}$), equation of best fit for the data in each row,
A = tyre pressure (kPa),
B = soil moisture content, w(%) wet weight,
p_d = mean dry bulk density (g/cc),
L = applied load per tyre (kN), and
r = correlation coefficient.

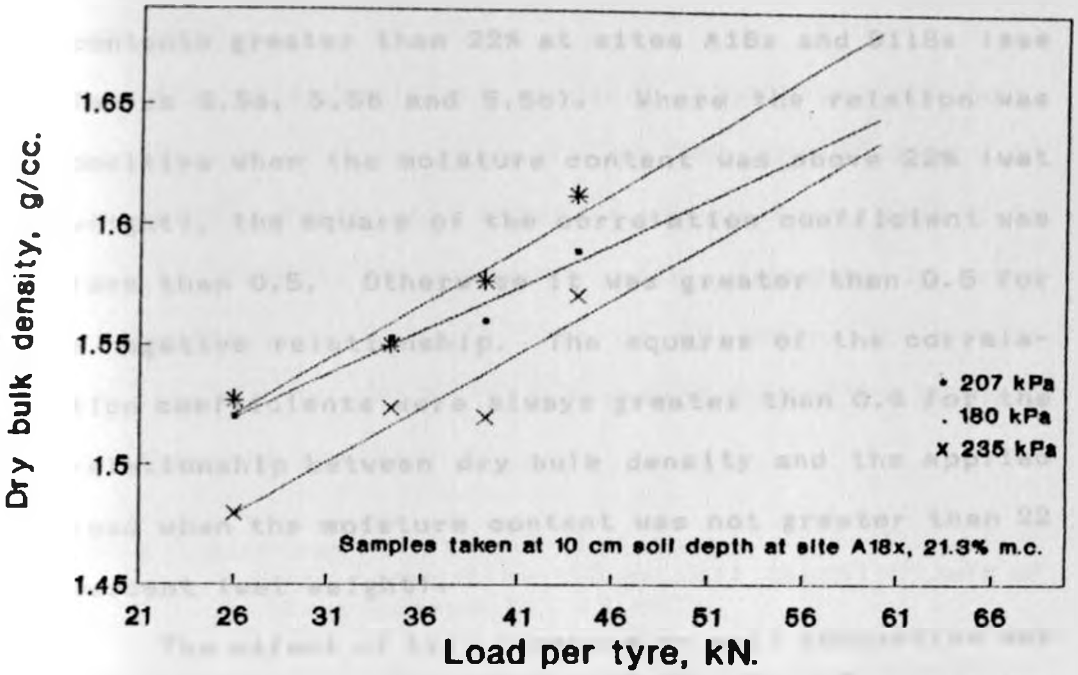


Fig. 5.3 Soil bulk density as affected by the applied load.

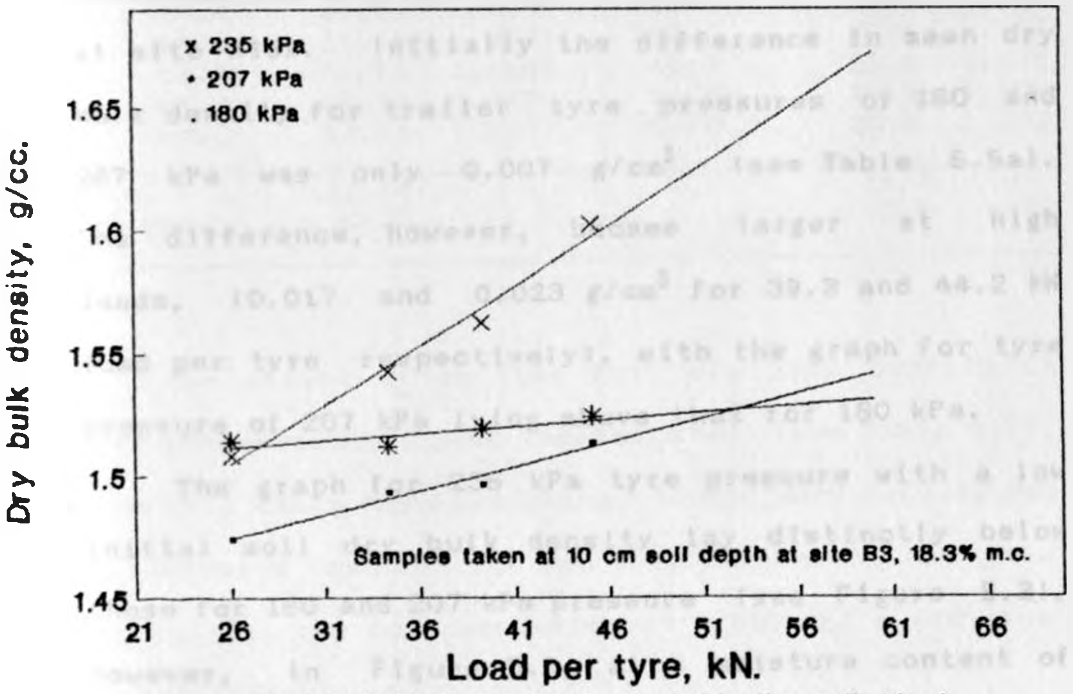


Fig. 5.4. Soil bulk density as affected by the applied load.

The relationships between mean dry bulk density and the applied load were inconsistent for moisture contents greater than 22% at sites A18x and D118x (see Tables 5.5a, 5.5b and 5.5c). Where the relation was positive when the moisture content was above 22% (wet weight), the square of the correlation coefficient was less than 0.5. Otherwise it was greater than 0.5 for a negative relationship. The squares of the correlation coefficients were always greater than 0.6 for the relationship between dry bulk density and the applied load when the moisture content was not greater than 22 percent (wet weight).

The effect of tyre pressure on soil compaction was also investigated. Figure 5.3 shows graphs relating bulk density and load per tyre at different tyre pressures for a moisture content of 21.3% (wet weight) at site A18x. Initially the difference in mean dry bulk density for trailer tyre pressures of 180 and 207 kPa was only 0.007 g/cm^3 (see Table 5.5a). The difference, however, became larger at high loads, (0.017 and 0.023 g/cm^3 for 39.3 and 44.2 kN load per tyre respectively), with the graph for tyre pressure of 207 kPa lying above that for 180 kPa.

The graph for 235 kPa tyre pressure with a low initial soil dry bulk density lay distinctly below those for 180 and 207 kPa pressure (see Figure 5.3). However, in Figure 5.4, at a moisture content of 17.2% (wet weight), the graph for 235 kPa tyre pressure with a high initial soil dry bulk density separated from and lay above those for 180 and 207 kPa inflation pressures.

At high moisture content the mean dry bulk density for a tyre pressure of 207 kPa (Table 5.6) decreased. Where soil moisture was uniform, soil bulk density tended to increase with increase in load application, (see Table 5.6) as evidenced by a tyre pressure of 180 kPa with a standard deviation of 0.72 for moisture content.

Table 5.6. Effect of soil moisture distribution on soil compaction (10 cm soil depth) at one of the experimental sites

Tyre pressure (kPa) 180					207
Load/tyre (kN)	m.c	b.d	Load/tyre (kN)	m.c	b.d
26.0	21.85	1.3680	39.3	19.3	1.493
34.4	21.88	1.3727	26.0	20.5	1.467
39.3	21.92	1.4263	45.2	20.9	1.373
45.2	22.56	1.3400	34.4	22.1	1.409
00.0	23.53	1.3677	00.0	25.8	1.297
Mean	22.35			21.7	
Std Dev.	0.72			2.5	

The effect of initial soil dry bulk density on soil compaction was also investigated (see Table 5.7). From this table the mean change in dry bulk density due to increased load application were 0.035 and 0.099 g/cm^3 for initial dry bulk densities of 1.480 and 1.410 g/cm^3 respectively.

Table 5.7. Effect of initial dry bulk density on soil compaction (10 cm soil depth) at site B3

	moisture (%)		b.d (g/cc)		$D_f - D_0$	
L (kN)	20.8	20.9	20.8	20.9	20.8	20.9
0.0	21.0	21.6	1.480	1.410		
26.0	21.5	21.0	1.463	1.482	-0.017	0.072
34.4	21.2	20.3	1.487	1.535	0.007	0.125
40.2	20.1	20.2	1.524	1.508	0.044	0.098
44.2	20.2	21.2	1.587	1.512	0.107	0.102
Mean	20.8	20.9			0.035	0.099

D_f = dry bulk density after treatment
D_0 = initial dry bulk density
L = load per tyre, kN.

The effect of axle load on mean dry bulk density for the two soils is shown in Figure 5.5. Mean dry bulk density increased with axle load application.

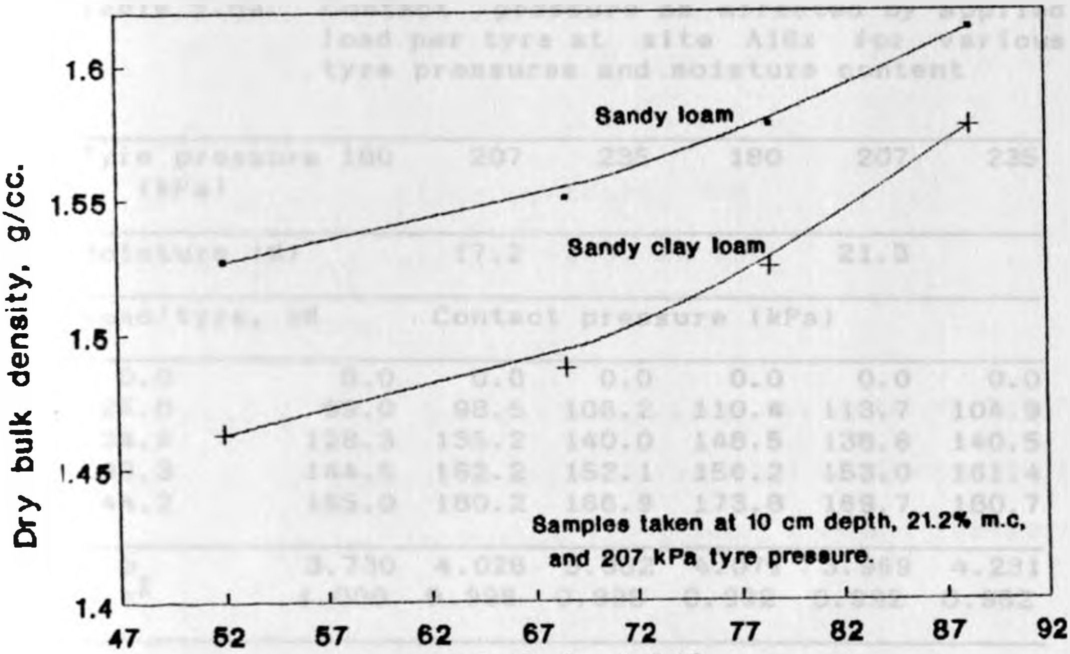


Fig.5.5. Soil bulk density as affected by applied load.

The graph for the brown sandy loam soil of site A18x lay above that for the sandy clay loam soil at site B3. The change in mean dry bulk density from one axle loading to another was fairly uniform for the two soil types.

The relationship between ground contact pressure and the applied load per tyre was investigated. The results are shown in Tables 5.8a and 5.8b. The contact pressure data in each tyre pressure column was related to the applied load by Equation 5.2. A regression analysis as described by Little and Hills (1978) was performed to determine the constant b in the equation and the corresponding correlation coefficient. The results are also shown in Tables 5.8a and 5.8b.

Table 5.8a. Contact pressure as affected by applied load per tyre at site A18x for various tyre pressures and moisture content

Tyre pressure (kPa)	180	207	235	180	207	235
Moisture (%)	17.2			21.3		
Load/tyre, kN	Contact pressure (kPa)					
0.0	0.0	0.0	0.0	0.0	0.0	0.0
26.0	99.0	98.5	106.2	110.4	113.7	104.9
34.4	128.3	135.2	140.0	148.5	138.6	140.5
39.3	144.6	162.2	152.1	156.2	153.0	161.4
44.2	165.0	180.2	166.9	173.8	169.7	180.7
b	3.730	4.026	3.982	4.071	3.969	4.231
r^2	1.000	0.996	0.998	0.992	0.992	0.982

Table 5.8b. Contact pressure as affected by applied load per tyre at site B3 for various tyre pressures and moisture content

Tyre pressure (kPa)	180	207	235	180	207	235
Moisture (%)		18.3			20.8	
Load/tyre, kN			Contact pressure (kPa)			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
26.0	99.0	98.3	108.6	104.9	92.9	95.6
34.4	134.8	129.2	127.0	141.9	113.6	122.7
39.3	148.7	136.8	138.0	149.8	133.5	133.5
44.2	167.1	158.1	153.6	186.9	153.6	161.3
b	3.787	3.954	3.954	4.032	3.402	3.537
r^2	0.998	0.994	0.978	0.994	0.998	0.998

b = constant in (CP = bL), best fit equation for the data in each column.
CP = contact pressure, kPa
L = applied load per tyre, kN.
r = coefficient of correlation.

$$CP = bL \qquad \ldots\ldots 5.2$$

where:

CP = ground contact pressure, kPa

L = applied load per tyre, kN and

b = constant

Figure 5.6 was derived using the data of Table 5.8a. It is seen from this figure that an increase in the load applied increased the ground contact pressure linearly.

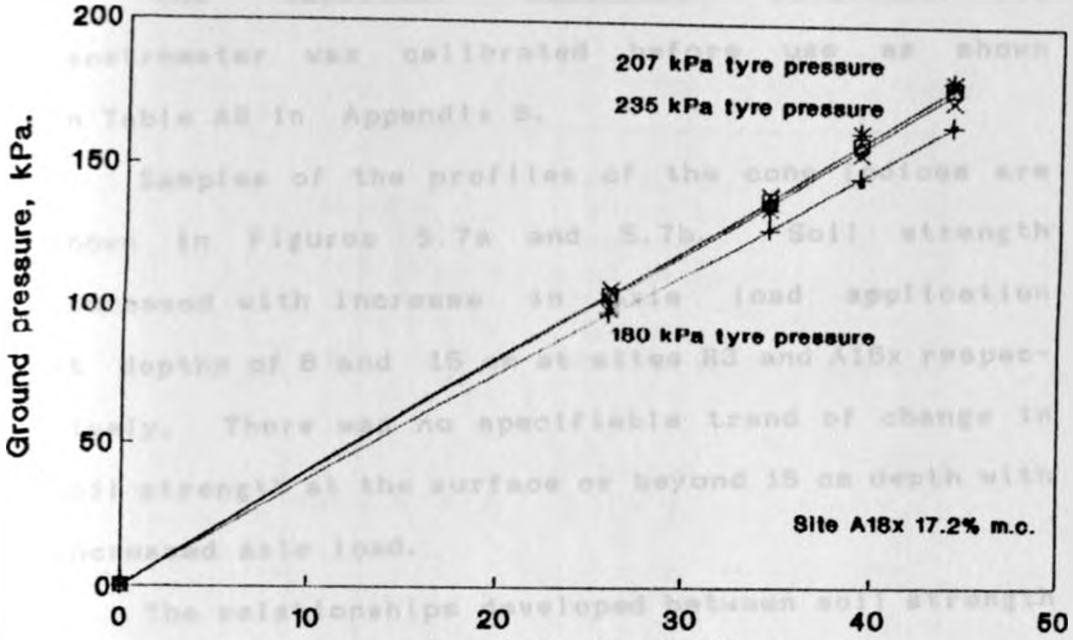


Fig. 5.6. Contact pressure as affected by the applied load.

The graphs for tyre inflation pressures of 180 and 235 kPa were on average higher than, but not distinctly separate from, that for 207 kPa pressure. This implies that for the same axle load application higher ground contact pressures were developed for 180 and 235 kPa than 207 kPa tyre inflation pressures.

5.4. Cone Index Distribution

Whereas the dry bulk density method was laborious and time consuming, the use of a cone penetrometer facilitated an alternative approach to the establishment of safe axle loads. However, cone index values are affected by soil moisture content. It was found that initial soil strength affected the constants in the empirical equations developed. The penetrometer was calibrated before use as shown in Table A8 in Appendix 8.

Samples of the profiles of the cone indices are shown in Figures 5.7a and 5.7b. Soil strength increased with increase in axle load application at depths of 8 and 15 cm at sites B3 and A18x respectively. There was no specifiable trend of change in soil strength at the surface or beyond 15 cm depth with increased axle load.

The relationships developed between soil strength and the compacting effort was investigated. The results are shown in Tables 5.9a and 5.9b. Equation 5.3 was used to relate cone index and the applied ground contact pressure for each tyre pressure. The constants a and b, and the coefficient of correlation were determined from a curvilinear analysis.

$$CI = a\ e^{bP} \qquad \text{..... 5.3}$$

where:

CI = cone index, kPa

P = ground contact pressure, kPa

a, b = constants.

Figure 5.8 represents one such relationship. The figure shows that an increase in compacting pressure increased soil strength. When compared to bulk density and the applied load relationship, the rela-

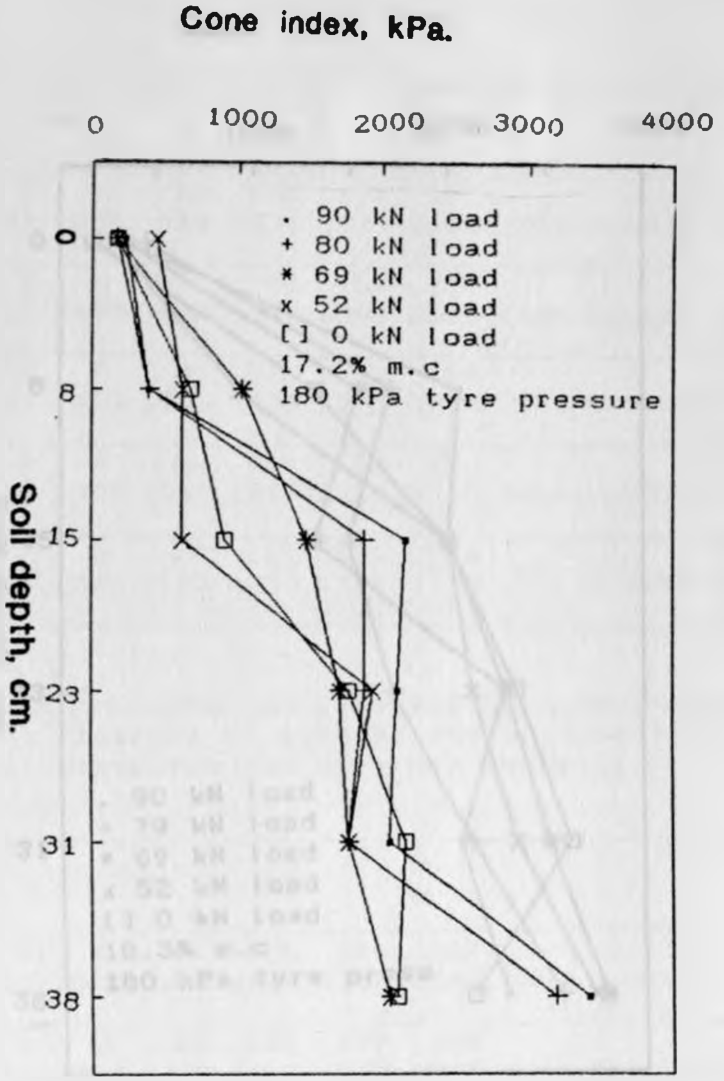


Figure 5.7a. Profiles of cone indices for various load applications at site A18x.

tionship between cone index and compacting pressure give better correlation coefficients even when the initial soil strength is considered.

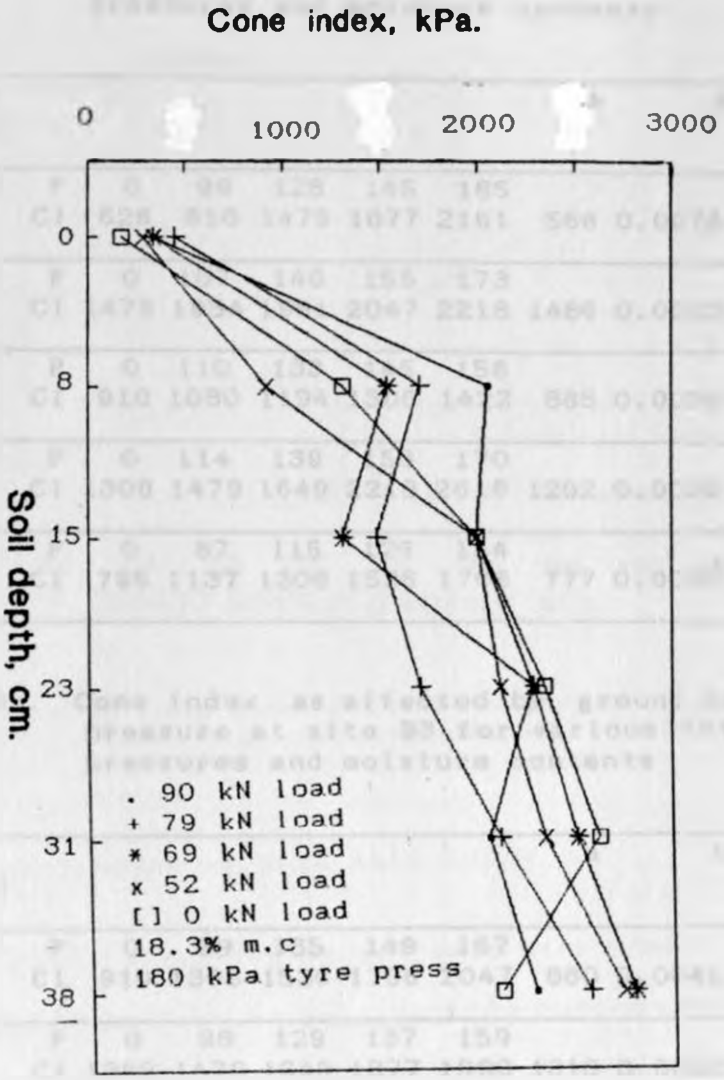


Figure 5.7b. Profiles of cone indices for various load applications at site B3.

Table 5.9a. Cone index as affected by ground contact pressure at site A18x for various tyre pressures and moisture contents

m.c (%)	i.p (kPa)							a	b	r^2
17.2	180	P	0	99	128	145	165			
		CI	626	910	1479	1877	2161	566	0.0076	0.903
17.2	235	P	0	107	140	155	173			
		CI	1479	1934	1991	2047	2218	1486	0.0022	0.980
21.0	180	P	0	110	133	145	156			
		CI	910	1080	1194	1308	1422	885	0.0026	0.878
21.3	207	P	0	114	139	153	170			
		CI	1308	1479	1649	2218	2616	1202	0.0035	0.663
21.0	235	P	0	87	115	126	154			
		CI	796	1137	1308	1536	1706	777	0.0050	0.974

Table 5.9b. Cone index as affected by ground contact pressure at site B3 for various tyre pressures and moisture contents

m.c (%)	i.p (kPa)							a	b	r^2
18.3	180	P	0	99	135	149	167			
		CI	910	1308	1536	1706	2047	880	0.0045	0.960
18.3	207	P	0	98	129	137	159			
		CI	1365	1479	1649	1877	1990	1310	0.0022	0.782

a, b = constants in ($CI = ae^{bP}$) equation relating cone index and ground contact pressure,
CI = cone index in kPa,
P = ground contact pressure in kPa,
r = coefficient of correlation,
i.p = tyre inflation pressure, and
m.c = soil moisture content.

give better correlation coefficients even when the initial soil strength is considered.

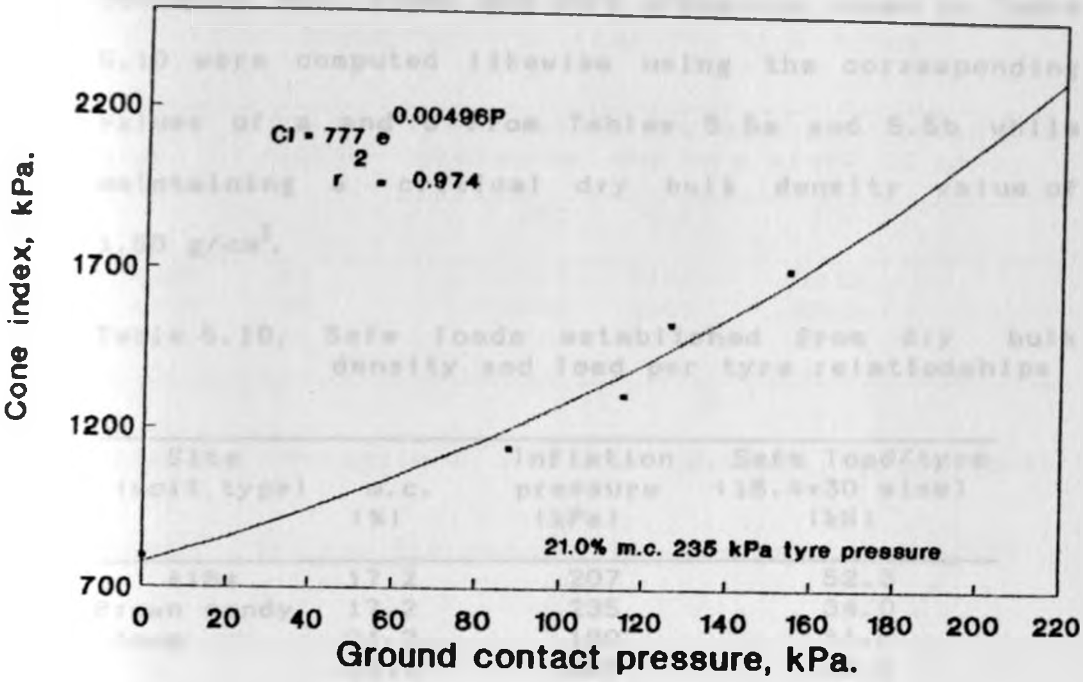


Fig. 5.8. Cone index as affected by ground contact pressure at site A18x.

5.5. Establishment of Safe Axle Loads

Table 5.10 shows the established safe loads for an 18.4x30 tyre based on the relationship between dry bulk density and the applied load per tyre. As an example, the safe load when the soil moisture content was 17.2 percent for a tyre pressure of 207 kPa at site A18x (see Table 5.5a) was determined as follows. At this tyre pressure the values of a and b are 1.423 and 0.002 (respectively). From Table 2.2 a critical dry bulk density value of 1.58 g/cm^3 is used to compute the safe load. Inserting these values of a, b and p_b in Equation 5.1 a safe load per tyre of 52.3 kN is computed. Safe loads at the other soil moisture contents, soil types and tyre pressures shown in Table 5.10 were computed likewise using the corresponding values of a and b from Tables 5.5a and 5.5b while maintaining a critical dry bulk density value of 1.58 g/cm^3.

Table 5.10. Safe loads established from dry bulk density and load per tyre relationships

Site (soil type)	m.c. (%)	Inflation pressure (kPa)	Safe load/tyre (18.4x30 size) (kN)
A18x	17.2	207	52.3
Brown sandy	17.2	235	34.0
loam	21.3	180	41.6
	21.3	207	38.4
	21.3	235	47.3
B3	18.3	235	41.6
Brown sandy	20.8	180	46.1
clay loam	20.8	207	51.5
Mean			44.1

Tyre load limits at various inflation pressures are shown in Table 5.11. The computed mean safe load per tyre was 44 kN. Comparison of Tables 5.10 and 5.11 shows that the established safe loads per tyre ranged from 1.23 to 1.89 times the load limit at 180 kPa inflation pressure.

Using the established safe load per tyre of 44 kN, Equation 5.2 and the appropriate value of the constant b from Tables 5.8a and 5.8b, safe contact pressures shown in Table 5.12 with a mean of 174 kPa were computed.

Table 5.11. Tyre inflation pressures (kPa) for various loads (kg) for traction-type tyres

Tyre size	Ply rating	Tyre loads at various cold inflation pressures, maximum speed 32 km/h		
		152	166	180
18.4x28	10	2477	2609	2732
18.4x30	10	2559	2691	2822
18.4x30	10	2713	2854	2991

Loads and inflations are for maximum speeds up to 32 km/h.

Source: Tire and Rim Association (Traux et al., 1985).

Table 5.12. Safe ground contact pressures established from dry bulk density and ground contact pressure relationships

Site (soil type)	m.c. (%)	Inflation pressure (kPa)	Safe ground pressure (kPa)
A18x	17.2	207	177
Brown sandy	17.2	235	175
loam	21.3	180	179
	21.3	207	175
	21.3	235	186
B3	18.3	235	174
Brown sandy	20.8	180	175
clay loam	20.8	207	150
Mean			174

A statistical analysis on dry bulk density results was performed to determine whether the compaction due to the different loads applied were significantly different from non-treated sections (see Tables 5.13a to 5.13d). Different strips were used for the various ground contact pressures applications. As a result

Table 5.11. Tyre inflation pressures (kPa) for various loads (kg) for traction-type tyres

Tyre size	Ply rating	Tyre loads at various cold inflation pressures, maximum speed 32 km/h		
		152	166	180
18.4x28	10	2477	2609	2732
18.4x30	10	2559	2691	2822
18.4x30	10	2713	2854	2991

Loads and inflations are for maximum speeds up to 32 km/h.

Source: Tire and Rim Association (Traux et al., 1985).

Table 5.12. Safe ground contact pressures established from dry bulk density and ground contact pressure relationships

Site (soil type)	m.c. (%)	Inflation pressure (kPa)	Safe ground pressure (kPa)
A18x Brown sandy loam	17.2	207	177
	17.2	235	175
	21.3	180	179
	21.3	207	175
	21.3	235	186
B3 Brown sandy clay loam	18.3	235	174
	20.8	180	175
	20.8	207	150
Mean			174

A statistical analysis on dry bulk density results was performed to determine whether the compaction due to the different loads applied were significantly different from non-treated sections (see Tables 5.13a to 5.13d). Different strips were used for the various ground contact pressures applications. As a result variability in the initial soil bulk density occurred.

Table 5.13a. Soil dry bulk density (at 10 cm soil depth) as affected by compaction pressure (P), site A18x, 21.3% moisture content

P (kPa)	0.0	109.7	150.0	156.8	174.7
Replicates	Dry bulk density (g/cc)				
R1	1.5303	1.4898	1.5296	1.5603	1.5903
R2	1.4803	1.5301	1.5704	1.5403	1.5802
R3	1.5201	1.5406	1.5599	1.5796	1.6005
R4	1.5203	1.4698	1.5396	1.5704	1.6097
R5	1.5401	1.5001	1.5203	1.6597	1.6002
R6	1.5101	1.6096	1.5899	1.5010	1.6295
R7	1.4397	1.5004	1.5002	1.5501	1.5708
R8	1.4904	1.4005	1.5403	1.4703	1.5694
R9	1.4603	1.5396	1.5303	1.5406	1.5721
Mean	1.4991	1.5089	1.5423	1.5525	1.5914
t(p=0.05)		0.4451	2.9871	2.5559	7.0132

Table 5.13b. Soil dry bulk density (at 10 cm soil depth) as affected by compaction pressure (P), site A18x, 17.2% moisture content

P (kPa)	0.0	101.4	134.5	153.8	172.7
Replicates	Dry bulk density (g/cc)				
R1	1.4798	1.4304	1.4798	1.4799	1.5000
R2	1.4602	1.6103	1.5105	1.5001	1.5405
R3	1.4904	1.4204	1.4897	1.5400	1.5201
R4	1.4799	1.4304	1.5401	1.5195	1.6095
R5	1.4895	1.5499	1.4403	1.5703	1.5797
R6	1.4903	1.5398	1.5704	1.5000	1.5297
R7	1.5704	1.5803	1.5900	1.5798	1.6098
R8	1.5597	1.5501	1.5901	1.5997	1.5901
R9	1.5105	1.5698	1.5703	1.5927	1.6006
Mean	1.5034	1.5201	1.5312	1.5424	1.5644
t(p=0.05)		0.6113	1.2744	2.0071	3.2493

In Table 5.13a and 5.13b ground contact pressures used for each load applied are average values for the tyre inflation pressures of 180, 207 and 235 kPa.

Tabulated t(p=0.05) = 2.12 for 16 df.

Table 5.13c. Soil dry bulk density (at 10 cm soil depth) as affected by compaction pressure (P), site B3, 18.3% moisture content

P (kPa)	0.0	106.2	135.9	147.0	166.4
Replicates			Dry bulk density (g/cc)		
R1	1.4402	1.4505	1.4603	1.4666	1.5643
R2	1.5004	1.5300	1.4797	1.4700	1.5848
R3	1.4497	1.4399	1.5403	1.5524	1.3903
R4	1.5416	1.5374	1.5034	1.5186	1.5545
R5	1.4568	1.4755	1.4716	1.4813	1.5645
R6	1.5103	1.5298	1.5622	1.5565	1.4543
R7	1.4193	1.4704	1.6167	1.5380	1.5965
R8	1.5507	1.5327	1.5305	1.6013	1.5850
R9	1.4173	1.5219	1.6539	1.5461	1.6262
Mean	1.4763	1.4987	1.5354	1.5256	1.5467
t(p=0.05)		1.0487	2.1224	2.1723	2.3260

Table 5.13d. Soil dry bulk density (at 10 cm soil depth) as affected by compaction pressure (P), site B3, 20.8% moisture content

P (kPa)	0.0	101.8	130.9	144.7	173.9
Replicates			Dry bulk density (g/cc)		
R1	1.4590	1.4605	1.4910	1.5304	1.5698
R2	1.4908	1.5003	1.5201	1.4996	1.5901
R3	1.5099	1.4998	1.4704	1.5099	1.5501
R4	1.4702	1.4096	1.4502	1.5198	1.5498
R5	1.4704	1.5199	1.5690	1.5003	1.6304
R6	1.4990	1.4590	1.4403	1.5510	1.5801
R7	1.4897	1.4605	1.4404	1.5010	1.5310
R8	1.4805	1.4597	1.5710	1.4890	1.6197
R9	1.4390	1.5403	1.4603	1.4697	1.5110
Mean	1.4787	1.4788	1.4903	1.5079	1.5702
t(p=0.05)		0.0081	0.6182	2.7197	6.1016

In Table 5.13c and 5.13d ground contact pressures used for each load applied are average values for the tyre inflation pressures of 180, 207 and 235 kPa.

Tabulated t(p=0.05) = 2.12 for 16 df.

The established ground pressures beyond which induced soil compaction was considered significant at 5 percent confidence level are shown in Table 5.14. The mean ground pressure was 146.3 kPa and it was approximated to 150 kPa.

Table 5.14. Ground contact pressures above which induced soil compaction is significant

Site/soil	Ground contact pressures (kPa)	
A18x/sandy loam	154(17.2% m.c.)	150(21.3% m.c.)
B3/sandy clay loam	136(18.3% m.c.)	145(20.8% m.c.)
		Mean 146

A statistical analysis on cone index results was performed to determine whether the compaction due to the applied compacting ground pressure was significantly different from non-treated sections (Table 5.15a to 5.15c). The mean safe ground contact pressure was 136 kPa and it was approximated to 140 kPa.

Table 5.15a. Cone index as affected by ground contact pressure (P), site A18x, 17.2% moisture

P (kPa)	0.0	102.9	134.2	149.6	169.0
	Penetrometer dial reading				
	60	80	80	85	95
	70	90	95	95	100
	30	25	65	85	80
	25	55	65	80	110
Mean	46.25	62.50	76.25	86.25	96.25
t(p=0.05)		0.89	2.27	3.48	3.93

Tabulated t(p=0.05) = 2.447.

Table 5.15b. Cone index as affected by ground contact pressure (P), site A18x, 21.1% moisture

P (kPa)	0.0	103.5	142.1	153.6	160.1
	Penetrometer dial reading				
	55	75	70	100	120
	60	55	75	95	110
	30	55	60	80	65
	40	45	55	55	85
	25	50	50	60	45
	55	45	55	55	80
Mean	44.17	54.17	60.83	74.17	84.17
t(p=0.05)		1.33	2.32	2.93	3.12

Tabulated t(p=0.05) = 2.228.

Table 5.15c. Cone index as affected by ground contact pressure (P), site B3, 18.3% moisture

P (kPa)	0.0	98.7	132.0	142.8	163.0
	Penetrometer dial reading				
	65	65	65	100	85
	55	65	80	65	90
	30	55	75	80	75
	50	60	60	70	105
Mean	50.00	61.25	70.00	78.75	88.75
t(p=0.05)		1.45	2.31	2.69	4.01

Tabulated t(p=0.05) = 2.447.

Safe loads were established from a safe ground pressure of 150 kPa, and the relations between ground pressures and load per tyre were used, (see Tables 5.8a and 5.8b). As an example, at 207 kPa tyre pressure and a soil moisture content of 17.2% the value of b in Equation 5.2 is 4.026 (Table 5.8a). Using this equation and a safe ground contact pressure of 150 kPa, a safe load per tyre of 37.3 kN was computed.

Safe loads at the other soil moisture contents, soil type and tyre pressures shown in Table 5.16 were computed likewise using the appropriate value of b from Tables 5.8a and 5.8b. The average safe loads per tyre for an 18.4x30 tyre obtained were 37 kN and 40 kN at sites A18x and B3 respectively.

Table 5.16. Safe loads established from statistical analysis

Site(soil)	Inflation pressure kPa	m.c. (%)	Safe load per tyre (18.4x30) kN
A18x (sandy loam)	207	17.2	37.3
	235	17.2	37.7
	180	21.3	36.9
	207	21.3	37.8
	235	21.3	35.5
B3 (sandy clay loam)	235	18.3	37.9
	180	20.8	37.2
	207	20.8	44.1

5.6. Selection of Suitable Trailer Units

The data collected for the selection of suitable trailer units are shown in Tables 5.17 and 5.18. The tables show values of payloads and trailer axle loads for loaded single bundle and nucleus estate trailers.

Some data was recorded for a high capacity bin trailer (HCBT). This is shown in Table 5.19. The high capacity bin trailer had two axles and on average each axle carried a load of 7030 kg. The maximum recorded load per axle was 7585 kg.

Table 5.17. Payloads and axle loads in kg for SBTs.

Serial number	Reg. No	Tractor make and model	Weight of loaded vehicle in kg.	Payload (kg)	Axle load (kg) (loaded trailer)	Axle load (kg) (empty trailer)
1	KXL 450	Ford 5610 2WD	12740	6420	6530	2340
2	KUV 479	Same S 80 2WD	10790	5110	5260	2200
3	KUV 478	Same S 80 2WD	11140	5610	5100	2010
4	KZG 233	J. Deere 2250	11890	6240	5850	2120
5	KUV 476	Same S 80 2WD	12200	6640	6200	2050
6	KZG 935	J. Deere 2250	13460	7350	6300	2120
7	KXL 465	Ford 5610 2WD	11220	5390	5260	2120
8	KXL 456	Ford 5610 2WD	12470	6220	5950	2230
9	KYF 427	J. Deere 2250	11700	6010	5450	2100
10	KXL 458	Ford 5610 2WD	12870	6660	5920	2310
11	KZG 938	J. Deere 2250	11690	5420	5620	2410
12	KXL 365	J. Deere 2040	11270	5470	5200	2100
13	KXL 360	J. Deere 2040	10950	5200	5320	2120
14	KXL 470	Ford 5610 2WD	10130	4340	4660	2020
15	KZG 936	J. Deere 2250	12280	6150	5790	2200
16	KZG 934	J. Deere 2250	10240	4170	5350	2230
17	KUV 479	Same S 80 2WD	10110	**4430**	**4630**	**2200**
18	KXL 470	Ford 5610 2WD	12090	6300	5950	2020
19	KZG 935	J. Deere 2250	14290	8180	7350	2120
20	KZG 936	J. Deere 2250	14240	8110	7350	2200
21	KXL 361	J. Deere 2250	10300	4190	4900	
22	KXL 360	J. Deere 2250	11370	5620	5780	2120
23	KUV 473	Same S 80 2WD	11100	5430	5390	
24	KUV 476	Same S 80 2WD	10840	5280	4950	2050
25	KYF 427	J. Deere 2250	11880	6190	5720	2100
26	KYF 425	J. Deere 2250	11550	5440	6100	
27	KUV 482	Same S 80 2WD	11050	5360	5380	
28	KXL 361	J. Deere 2250	12830	6690	6650	
29	KZG 938	J. Deere 2250	12060	5790	6280	2410
30	KZG 936	J. Deere 2250	12300	6170	5700	2120
31	KXL 458	Ford 5610 2WD	12680	6470	6090	2310
32	KUV 473	Same S 80 2WD	11900	6230	6280	2150
33	KUV 476	Same S 80 2WD	10350	4790	4810	2050
					Mean	2161.786

Operators of the vehicles with some data missing forgot to stop by the weigh-bridge on their way out after sugarcane delivery.

Table 5.18. Payloads and axle loads in kg for NETs.

Serial number	Reg. No	Tractor make and model	Weight of loaded vehicle in kg.	Payload (kg)	Axle load (kg) (loaded trailer)	Axle load (kg) (empty trailer)
1	KZG 629	Same E 80 4WD	13120.00	6320.00	6950.00	2610.00
2	KWU 300	Same C 75 4WD	13030.00	6090.00	6930.00	2610.00
3	KWV 311	Same C 75 4WD	15650.00	8650.00	8960.00	2610.00
4	KWV 298	Same C 75 4WD	14760.00	7900.00	8180.00	2480.00
5	KZG 625	Same E 80 4WD	15190.00	8340.00	8560.00	2680.00
6	KZG 629	Same E 80 4WD	13540.00	6720.00	7310.00	2600.00
7	KWU 300	Same C 75 4WD	13480.00	6540.00	7370.00	2610.00
8	KWU 258	Same C 75 4WD	14200.00	7200.00	7700.00	2660.00
9	KZG 624	Same E 80 4WD	15180.00	7270.00	8720.00	2800.00
10	KZG 625	Same E 80 4WD	12340.00	5485.00	5490.00	2680.00
11	KWV 311	Same C 75 4WD	14800.00	7800.00	8220.00	2610.00
12	KWV 296	Same C 75 4WD	16260.00	9260.00	9320.00	2680.00
13	KZG 625	Same E 80 4WD	13600.00	6750.00	7550.00	2680.00
14	KZG 626	Same E 80 4WD	12530.00	5680.00	6830.00	2680.00
15	KZG 629	Same E 80 4WD	14100.00	7300.00	8200.00	2610.00
16	KXL 533	Same C 75 4WD	15970.00	8750.00	8950.00	2700.00
17	KZG 631	Same E 80 4WD	14040.00	6760.00	8050.00	3100.00
18	KZG 625	Same E 80 4WD	15250.00	8400.00	8630.00	2680.00
19	KXL 531	Same C 75 4WD	14410.00	7230.00	7820.00	2690.00
20	KWU 258	Same C 75 4WD	15020.00	8020.00	8410.00	2680.00
21	KZG 624	Same E 80 4WD	15430.00	8580.00	8730.00	2800.00
22	KXL 532	Same C 75 4WD	14030.00	6280.00	7910.00	3370.00
23	KWV 298	Same C 75 4WD	14100.00	7240.00	7610.00	2680.00
24	KWU 296	Same C 75 4WD	15650.00	8650.00	8830.00	2680.00
25	KZG 625	Same E 80 4WD	13520.00	6670.00	7500.00	2680.00
26	KWU 258	Same C 75 4WD	14400.00	7400.00	7850.00	2660.00
27	KWV 311	Same C 75 4WD	15010.00	8010.00	8880.00	2610.00
28	KWU 300	Same C 75 4WD	14020.00	7080.00	7690.00	2610.00
29	KXL 533	Same C 75 4WD	15800.00	8580.00	8900.00	2700.00
30	KWV 298	Same C 75 4WD	14550.00	7690.00	8020.00	2480.00
31	KZG 625	Same E 80 4WD	14520.00	7670.00	7900.00	2680.00
32	KWV 298	Same C 75 4WD	14970.00	8110.00	8340.00	2480.00
33	KZG 629	Same E 80 4WD	14700.00	7900.00	8390.00	2610.00
34	KZG 625	Same E 80 4WD	15010.00	8160.00	8580.00	2680.00
35	KWU 258	Same C 75 4WD	14350.00	7350.00	7820.00	2660.00
36	KWU 258	Same C 75 4WD	14990.00	7990.00	8390.00	2680.00
37	KXL 533	Same C 75 4WD	15690.00	8470.00	8810.00	2700.00
38	KZG 631	Same E 80 4WD	14200.00	6920.00	8150.00	3100.00
39	KXL 531	Same C 75 4WD	14410.00	7230.00	7840.00	2690.00
40	KXL 532	Same C 75 4WD	13990.00	6240.00	7870.00	3370.00
					Mean	2709.25

Table 5.19. Payloads and load per axle in kg for a high capacity bin trailer.

Tractor type	Axle load	Payload
Deutz-Far	6510	11830
•	6995	11830
Lamborghini 956	7585	12410

Table 5.20 shows compaction results from a trial using a HCBT at site B3 with a moisture content of 20.3%. A load per axle of 7585 kg was used in the trial. From this table, increase in bulk density values were 0.121 (after four passes) and 0.043 g/cm^3 (after three passes) at the surface and at 10 cm soil depth respectively. The data was not enough to be used for statistical analysis.

Table 5.20. Soil compaction results for a HCBT.

Depth (cm)	Vehicle passes 0	1	2	3	4
	Dry bulk density, g/cc				
0	1.402	1.480	1.493	1.471	1.535
10	1.507	1.500	1.551	1.550	1.523
20	1.543	1.566	1.447	1.436	1.479

Regression analysis performed on the data in Tables 5.17, 5.18, A9.1 and A9.2 gave the relations shown in Equations 5.4 and 5.5.

For a single bundle trailer:

$$Y = 0.524 X + 2618 \qquad \ldots\ldots 5.4$$

$$r^2 = 0.780$$

For a nucleus estate trailer:

$$Y = 0.760\ X + 2367 \qquad \text{.....}\ 5.5$$

$$r^2 = 0.874$$

where:

Y = loaded axle load in kg,

X = payload in kg and

r = coefficient of correlation.

Although these equations had high correlation coefficients (r^2 equal to 0.780 and 0.874 for equation 5.4 and 5.5 respectively), they did not represent the situation when the trailers were empty. The equations show that SBTs and NETs when empty on average developed 2618 and 2367 kg at the axle respectively. The measured empty trailer axle loads averaged 2150 and 2720 kg (Tables 5.17, 5.18, A9.1 and A9.2) for SBTs and NETs respectively. In order to represent these data more realistically, equations of the form shown in Equation 5.4 were developed. The Y axis intercepts were taken to be the average loads of 2150 and 2720 for SBTs and NETs respectively. The slope value was determined by the trial and error method shown in Tables A9.3 and A9.4. The coefficient whose sum of differences between estimated and measured trailer axle loads approached zero was chosen to be the best representative for the equation developed. Equations 5.6 and 5.7 were developed using this approach.

For a single bundle trailer:

$$Y = 0.599\ X + 2150 \qquad \ldots\ldots\ 5.6$$

For a nucleus estate trailer:

$$Y = 0.7125\ X + 2720 \qquad \ldots\ldots\ 5.7$$

where:

Y = loaded trailer axle load in kg, and

X = payload in kg.

For the same payload a single bundle trailer induced a lower trailer axle load than the nucleus estate trailer.

The mean and standard deviations of the payloads and axle loads are shown in Table 5.21.

Table 5.21. Mean and standard deviation for loaded trailer axle loads and payloads (kg)

Trailer type	Mean		Std. Dev.	
	payload	axle load	payload	axle load
NET	7377	7978	1013	824
SBT	6203	5867	1108	658

Table 5.21 shows that in general NETs carried higher payloads and induced higher axle loads than SBTs.

Equations 5.6 and 5.7 were used to compute the safe payloads to be carried by a SBT and a NET (Table 5.22).

Table 5.22. Payloads that would safely be carried by the trailers at various sites

Site/soil	SBT	NET
A18x/sandy loam	9000	6770
B3/sandy clay loam	10020	7630

5.7. The Proctor Test Results

The effect of moisture content on dry bulk density using various compaction efforts was investigated (see Figures 5.9a and 5.9b). Moisture content was varied from 6 to 24 percent on wet weight. Two types of soils were used: a brown sandy loam soil of site A18x and a brown sandy clay loam soil of site B3.

It was observed that dry bulk density increased up to a maximum then it decreased. Increased compaction pressure increased the dry bulk density (see Fig. 5.9a). Figure 5.9 shows that the dry bulk density values obtained in this test were greater than the critical value of 1.58 g/cm^3 for the soils of Mumias, (Table 2.2). The soils for site A18x were compacted more than those for site B3 for the same compaction pressure.

From Table 5.23 it is noticed that at optimum moisture content and a pressure of 108 kPa, the dry bulk density values at sites A18x and B3 were 1.884 and 1.798 g/cm^3 respectively. The average optimum moisture content was 19.5 percent (wet weight).

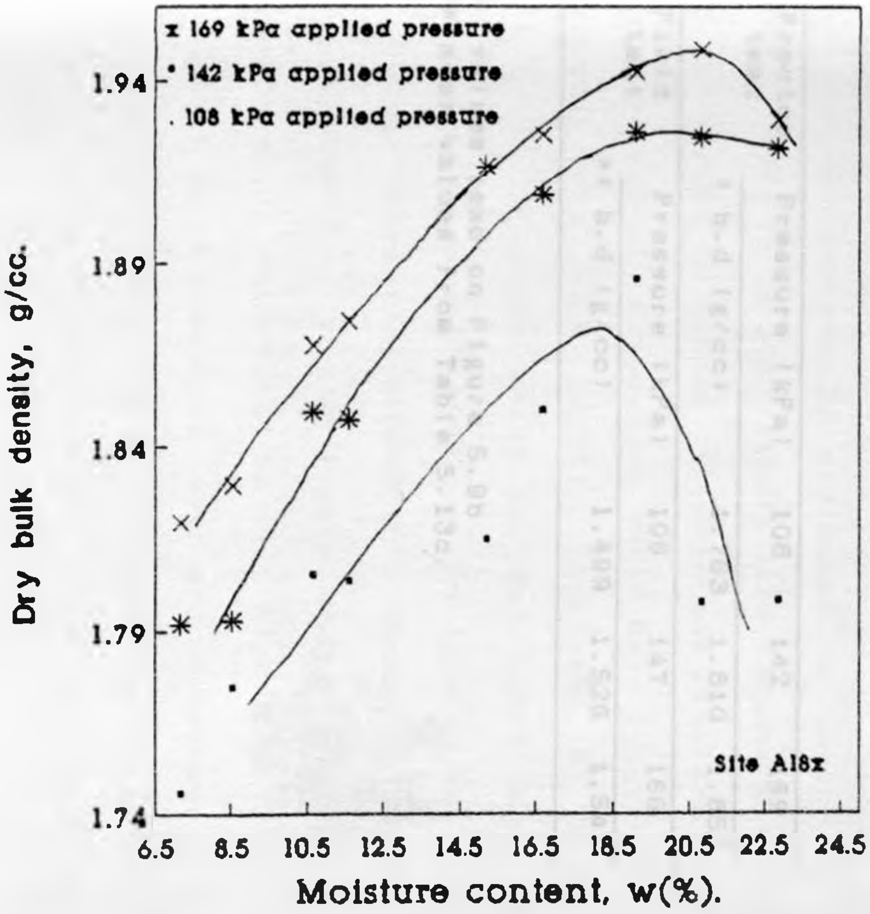


Fig. 5.9a. Dry bulk density as affected by soil moisture.

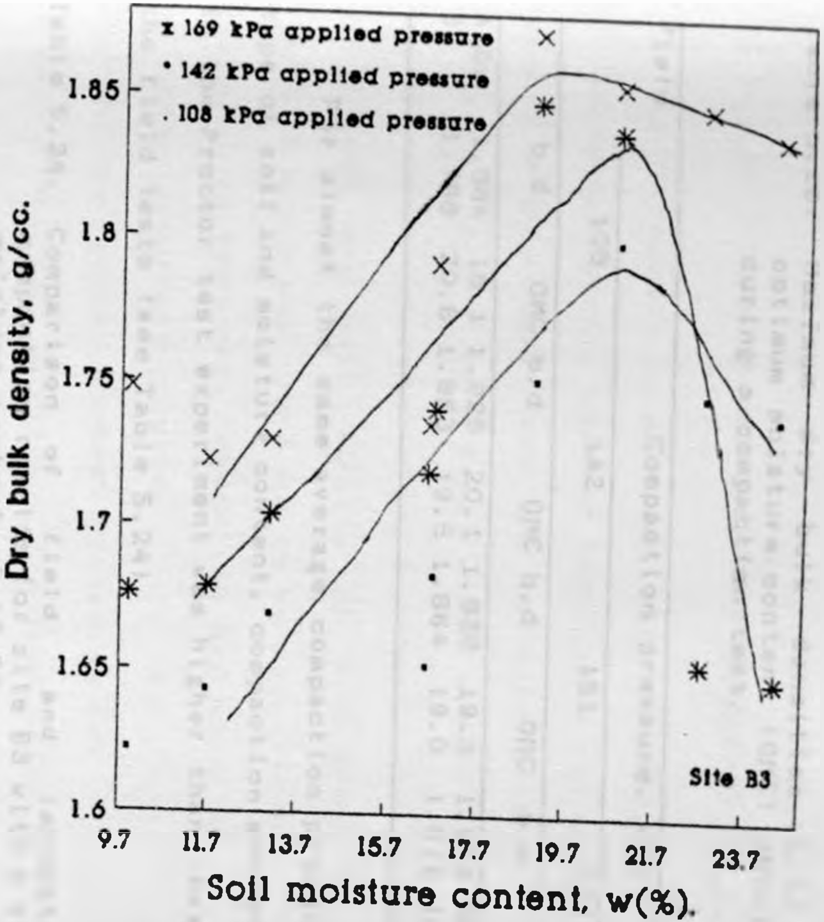


Fig. 5.9b. Dry bulk density as affected by soil moisture.

Table 5.23. Maximum dry bulk densities (b.d) and optimum moisture content (OMC) obtained during a compaction test.

Field	Compaction pressure, kPa							
	108		142		151		169	
	b.d	OMC	b.d	OMC	b.d	OMC	b.d	OMC
A18x	1.884	18.1	1.926	20.1	1.938	19.3	1.946	20.6
B3	1.798	20.8	1.853	19.5	1.864	19.0	1.872	18.8

For almost the same average compaction pressure, type of soil and moisture content, compaction achieved in the Proctor test experiment was higher than that in the field tests (see Table 5.24).

Table 5.24. Comparison of field and laboratory compaction results for site B3 with a soil moisture content of 18.3%

Proctor test	Pressure (kPa)	108	142	169
	* b.d (g/cc)	1.763	1.810	1.855
Field test	Pressure (kPa)	106	147	166
	** b.d (g/cc)	1.499	1.526	1.547

* values read on Figure 5.9b
** mean values from Table 5.13c.

6. DISCUSSION

6.1. Dry Bulk Density and Moisture Distribution

The difference in mean dry bulk density, for the top 30 cm soil layer, between trafficked and non-trafficked fields ranged from 0.2 to 0.24 g/cm^3. This difference in dry bulk density was significant at 5 percent confidence level using a t-test. The difference in mean dry bulk density of 0.03 g/cm^3 beyond 30 cm soil depth was found not to be significant. This shows that surface soil compaction had occurred in the trafficked sugarcane fields. This may have been a result of high ground contact pressures due to the high payloads carried by sugarcane transportation trailers at Mumias, which depend upon the inflation pressure and the soil deformation as explained by Taylor et al. (1986). Also it is most likely that induced axle loads did not exceed 10 tonnes (Ellwein and Froelich, 1989), otherwise subsoil compaction would have occurred. The mean soil dry bulk density increased by 0.24 to 1.59 g/cm^3, a value which is just above an average critical value of 1.58 g/cm^3 for the type of soils found in Mumias (Ferralic CAMBISOLS), Humbert (1968) and Buringh (1979). It is likely that sugarcane root development is restricted by this high bulk density.

For a 30 cm compacted layer and an average ploughing depth of 25.4 cm, 55 mm of compacted soil layer is left unploughed (Komba, 1990). This may lead to the formation of a hardpan after several cycles of ploughing. When a hardpan is present the development of sugarcane is affected because of a restricted root penetration, poor water infiltration rates and a rise in the water table especially in lowland fields. To avoid the formation of a hardpan the plough depth should be increased to 30 cm. It should be noted that an increase in ploughing depth will increase the cost of ploughing because of the increased draft. Consequently fuel consumption will also rise.

The moisture content for the soil layer between zero and 15 cm in traffic fields was lower than that in the non-trafficked fields. This may be attributed to the fact that in the layer between zero and 15 cm the evapotranspiration rate may have been higher for the canopy in trafficked as compared to non-trafficked fields. In addition the trafficked fields may have had a lower humus content than that in non-trafficked fields. High humus content enables a soil to retain more water. The trafficked fields may also have had a high rate of run-off than that in non-trafficked field. Compacted fields are prone to high run-off due to low infiltration rates. The soil moisture for the layer beyond 30 cm soil depth was unexpectedly higher in trafficked than that in non-trafficked fields. Due to hardpan formation in trafficked fields deep percolation may be impeded. The possible explanation to this observation is that in the layer beyond 30 cm soil depth, the deep rooting depth of the forest on the non-trafficked field as compared to the shallow sugarcane rooting depth on trafficked fields extracted water at this depth.

6.1.1. Possible Sources of Error

Soil compaction is normally affected by soil moisture content, type of soil, initial bulk density, intensity of loading and soil organic matter content. The results of this study were not affected by moisture content and type of soil. This can be attributed to the following. The differences in the proportions of sand, silt and clay for the soils of fields A8 and F was low yet the difference in dry bulk density was significant, (see Table 5.2). Similarly the difference in proportions of sand, silt and clay for field sites A8 and A10 was high yet there was hardly any difference in bulk densities at the two sites.

However, the difference in bulk density values may have resulted from the following:

(i) There was little soil disturbance across the core but there may have been some problems with compression of the core a possibility reported by Wells (1959).

(ii) The different fields may have had different organic matter content.

6.2. Soil Response to Compacting Loads

When the soil moisture contents was less than 22 percent, dry bulk density increased steadily with increase in axle load application. This can be attributed to the fact that more energy became available which weakened the bonding between the soil particles thereby enabling the soil particles to rearrange themselves as they were forced together. This in turn caused a reduction in the volume of the soil and an increase in the dry bulk density until a limit was attained at about 22% moisture, (Section 3.1.3).

There was no trend in the change in soil strength at the surface or beyond 15 cm depth when the axle load was increased. This may be attributed to the fact that there may have been substantial varied amounts of humus at the soil surface which acted as a cushion to compacting loads and led to different soil responses to compacting loads. At depths greater than 15 cm the compacting load was not effective. The different soil strength values recorded may have been due to variation in soil structure. Cone indices increased exponentially with increase in axle load application at depths of 8 and 15 cm at sites B3 and A18x respectively. The influence of variations in soil water content and organic matter may have been minimal and therefore increase in soil strength was basically due to the applied compacting load.

At higher moisture contents the resulting soil compaction was rather erratic with increased axle load application. Wheel rutting occurred. Perhaps the soil was in either a plastic or liquid state whereby it would offer no resistance to deformation when subjected to a compacting load.

Compaction due to use of tyre inflation pressure of 180 and 207 kPa were not different at low axle load. At high axle loads (greater than 75 kN per axle) the graph for a tyre pressure of 207 kPa lay above that for 180 kPa. The possible explanation to this observation is that high axle loads induced high ground contact pressures which in turn increased soil compaction. For a 180 kPa tyre inflation pressure the trailer tyre was less rigid than at 207 kPa pressure. At high axle loads and low inflation pressures the tyre walls flexed thereby causing the area of contact to increase. This in effect reduced the ground contact pressure and as a result the soil was less compacted.

The graph for a tyre pressure of 235 kPa at certain instances was lower than the graphs for 180 and 207 kPa while at others it was higher. The discrepancy was due to the initial soil bulk density which seemed to have had a greater effect on soil compaction than the tyre pressures. This implies that within the limits of the experimental errors and axle load application any of the inflation pressures can be employed. However, the consequences of using low or high inflation pressures must be considered before choosing the appropriate value to use.

For the same axle load application compaction in a brown sandy loam soil at site A18x was higher than that at site B3 (brown sandy clay loam soil). This was because site A18x had a high initial bulk density due to the presence of gravel. The effect of high axle loads on soil compaction in the sandy loam and sandy clay loam soils were not distinctly different. Therefore soil type did not influence soil compaction.

6.2.1. Possible Sources of Error

The compaction due to different load applications may have been affected by non-uniformity of soil moisture, soil structure and organic matter content. The method of load application may also have affected the soil compaction. Soil moisture variations may have been due to local variations in organic matter content, water infiltration rates, and the water transmission and retention capacity of the soil.

6.3. Ground Pressure and Axle Load Relationships

A rise in axle load increased ground contact pressure linearly. As the axle load increased the change in tyre contact area may have been slight such that the influence of area of contact on ground contact pressure was negligible. The area of contact did not change much perhaps because the ground was soft. This made the tyre sink, flexing little or not at all when the compacting load increased.

It was not possible to detect any small changes in the area of contact as the axle load was increased. This is because the method used to determine the area of contact could not detect such differences.

For the same axle load application, ground contact pressures developed by a tyre with 180 or 235 kPa inflation pressure were higher than those developed by a tyre with 207 kPa pressure. This is contrary to the expected observation where the order of the ground contact pressures developed for the three tyre inflation pressures should be high for 235 and least for 180 kPa. Errors in experimentation especially the measurement of contact area might have been the cause of the discrepancy. Another error could have been due to differences in initial soil bulk density. A high initial soil bulk density provides a high resistance to tyre compaction than a low one. The area of contact for the same axle load, tyre type and size will be greater for a soil with low initial bulk density than for one with a high initial bulk density.

6.4. Establishment of Safe Axle Loads

For moisture contents between 17 and 21 percent (wet basis), when compaction is maximum, a safe ground contact pressure of 174 kPa was established from axle load and ground contact pressure relationships for a critical soil dry bulk density of 1.58 g/cm^3 (Table 2.2). This corresponded to a mean safe load per tyre of 44 kN, a value which is more than one and a half times the load limit of 27.7 kN at 180 kPa tyre pressure (Traux et al., 1985). The relationships between axle load and bulk density seem to have overpredicted the results. However, at high tyre pressures, for example 207 kPa that is used at Mumias, the load limit per tyre would be greater than at 180 kPa tyre pressure. Therefore when higher inflation pressures are employed it is possible to approach permissible loads per tyre close to the ones established in this research.

Based on statistical significance a mean safe ground pressure of 150 kPa was established when bulk density and cone index results were considered. Average loads per tyre for an 18.4x30 tyre of 37 kN and 40 kN were computed for sites A18x and B3 (respectively). These values, although less than the 44 kN safe load established from axle load bulk density relationships, they are still higher than the permissible load of 27.7 kN at 180 kPa cold inflation.

6.5. Selection of Suitable Trailer Units

Increased payload increased induced trailer axle load and for the same payload a single bundle trailer induced a lower trailer axle load than the nucleus estate trailer. The most obvious reason for this observation is that SBTs are lighter in build than NETs. Physical observation as shown in Plates 2 and 3 indicate that a NET has more frames than a SBT. This increases the weight of the former. Another possible explanation is that the centre of gravity for the SBT is closer to the tractor rear than that for the NET. This would mean that for the same axle load the SBT transfers more weight to the tractor and less to the trailer axle than the NET.

In reference to induced axle loads the SBT offered a superior design than the NET. This is because low axle loads were developed for the same payload for a SBT than a NET. The difference between the two mean axle loads for SBTs and NETs was found to be highly significant at a 5 percent confidence level. The mean payload for NETs was significantly higher than that for SBTs. Therefore there is need to either increase the carrying capacity of SBTs or increase the density of sugarcane stacks they carry.

The mean safe ground contact pressure of 174 kPa computed from mean dry bulk density and axle load relationships was unrealistic because other research findings show that such a pressure should be used for dry soils (see Table 2.1), Trouse and Humbert (1968), Dias and Nortcliff (1984) and, Ellwein and Froelich (1989).

From statistical analysis it was found that when ground contact pressures exceeded 150 kPa the induced soil compaction was significant at 5 percent confidence level. When this pressure and the developed empirical equations were used to calculate the safe axle loads, values of 74 (7543 kg) and 80 (8155 kg) kN at sites A18x (sandy loam) and B3 (sandy clay loam) respectively were obtained. Although these values were higher than the load limit of 55.4 kN at 180 kPa cold inflation, they were considered reasonable. This is because in normal sugarcane transport operations at Mumias, high inflation pressures are used. The load requirements for these pressures would definitely be higher than the requirement at 180 kPa pressure and may perhaps be close to safe axle loads established from this research.

Table A9.3 shows that single bundle trailers did not developed axle loads in excess of the established safe axle loads (7543 kg at site A18x and 8155 kg at site B3). This implies that the present SBTs do not induce significant soil compaction at sites A18x (lowland with a sandy loam soil) and B3 (upland with a sandy clay loam soil). Table A9.4 on the other hand shows that out of a total number of 60 NETs studied, 43 (72%) had axle loads exceeding the 7543 kg safe axle load for site A18x while 18 (45%) exceeded the 8155 kg level for site B3. NETs certainly cause significant soil compaction in fields with similar conditions as site A18x. However, there is a 55% chance that compaction caused by NETs in fields with similar conditions as site B3 is not significant.

When Tables 5.22 and 5.23 are compared it is noticed that SBTs from both lowland and upland fields carry far below the safe loads. Therefore there is room for increasing their carrying capacities up to a possible maximum of 7300 kg (sum of mean payload and corresponding standard deviation, Table 5.22). However, to carry up to the safe payload a new design of SBTs should be developed. On the other hand NETs from upland fields carry on average, payloads slightly below the safe loads while those from lowland fields carry slightly above these safe loads. There is need therefore to control the amount of sugarcane loaded on these trailers so that they operate within the safe range.

The maximum recorded load per axle of 7585 kg for the high capacity trailer is slightly above the established safe axle load at site A18x but it is well below the established safe axle load at site B3. The HCBT does not therefore cause significant soil compaction at site B3 but it may at site A18x.

6.6. The Induced Compaction in the Proctor Test

The Proctor test results indicated that as moisture content increased for any applied compaction pressure, dry bulk density increased up to a maximum then it decreased thereafter. This may be attributed to the fact that the bonds between the soil particles are weak, and are therefore sensitive to any variation of water content. As water was added to the soils there was a loss in strength. This made the compaction of the soil increase as the resistance offered by the soil particles to the compacting force was reduced. Soil deformation before the optimum moisture content was inelastic. As moisture content increased to the vicinity of the optimum value, the soil became highly elastic such that an increase on load may have compacted the soil, but on removal of the load the particles rebound to their original positions. When the moisture was increased beyond the optimum, compaction was achieved only if water was squeezed out.

The soils for site A18x (sandy loam) got compacted more than those for site B3 (sandy clay loam) for the same compaction pressure. This observation can be explained three fold. First, the structural arrangement of the two soils is different such that when a given compaction effort is applied, the soil particles for A18x get closer than B3. Second, the degree of bonding between adjacent particles for the soil of A18x seems to be weaker than that of B3. This implies that the structure for the soil in A18x is, comparatively, easier to fracture enabling the soil grains to rearrange better when a compaction load is applied. Third, particle size distribution and composition of the two soils may be different. The soil at site B3 may be more well-graded than that at site A18x. A well-graded soil does not get easily compacted because it offers a high resistance to shear-induced motion as compared to a poorly-graded soil.

The average optimum moisture content for the soils studied was 19.5 percent (wet weight). This value was within the moisture range of 17 and 21% used during the field tests. Therefore maximum compaction was attained. The fear that detrimental soil compaction occurs under all soil conditions that can be considered wet is thus eliminated.

For the same average compaction pressure, type of soil and soil moisture content, compaction achieved in the Proctor test experiment was higher than that in the field treatments. This may be attributed to the fact that the unconfined loading in the field treatments develops shear, normal and horizontal stresses. The soil particles got compressed and moved sideways due to these stresses. Consequently low soil compaction was attained.

On the other hand the confined static loading used in the Proctor test mainly produced a normal stress which lead to high soil compaction. Sideways soil particle movement was limited.

Second, uniformity in soil moisture content and soil structure due to remoulding in the Proctor test as compared to field treatments may have affected the resulting compaction. Third, the presence of some trash and organic matter in the fields may have lowered the compaction pressure. This may have led to low soil compaction.

6.6.1. Possible Sources of Error

Numerous factors influence soil compaction. In this test any temperature variations were due to changes in the weather. This is because the test lasted about nine hours each day. The size of the compaction mould was kept constant at 1000 cm^3. The distribution of the compaction pressure on any layer was kept fairly constant. There may have been variation in the amount of soil used on each layer compacted. The period, 24 hours, of curing was long enough. However, processing errors may have occurred as a result of mixing the soil by hand. Friction between the soil and the cylinder wall could have contributed to statistical errors at lower moisture contents.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Implications of carrying high payloads

1. More powerful tractors may be required to tow the high capacity trailers developed.
2. To support the developed high axle loads more rigid tyres with high ply rating and high tyre pressures may be required.
3. There would probably be frequent delays in the delivery of sugarcane to the factory during wet months because of bogging down of the vehicles.
4. The same amount of sugarcane will be delivered to the factory with fewer vehicles if transport operations are not interfered with.
5. If the existing trailers have to be modified a careful consideration of the design is required. This is because points of weakness may develop when the trailer capacity is increased.
6. With fewer vehicles operating:

   (a) a smaller number of operators will be required thus some costs will be reduced.

   (b) the vehicles will transverse the fields less and hence there will be less incidence of compaction.

   (c) repair and maintenance costs are likely to be high because of over use of the available vehicles.

   (d) the chances of reducing the percentage available vehicles are high. However, with an efficient Field Workshop this can be avoided.

7.2. Conclusions

1. There is evidence of significant soil compaction in the fields with traffic influence in the soil layer between 0 and 30 cm. This level of soil compaction may have contributed to yield losses of 5 to 10 percent reported in earlier reports at Mumias.

2. (i) It was found that for soil moisture contents between 17 and 21 percent (wet weight) ground contact pressures beyond 150 kPa (22 psi) caused significant soil compaction. This pressure corresponded to payloads of about 9000 and 6770 kg carried by single bundle and nucleus estate trailers (respectively), on 18.4x30, 10 ply rated tyres for tyre pressures between 180 and 235 kPa. The induced axle loads were 74 and 80 kN for fields with similar soil conditions as sites A18x (lowland with sandy loam soil) and B3 (upland with sandy clay loam soil) respectively.

   (ii) Maximum soil compaction occurs at moisture contents of about 20 percent (wet weight).

   (iii) It was found that non-uniformity of the initial soil strength and soil moisture content greatly affected uniformity in soil compaction.

(iv) It was not possible to differentiate between the influences on soil compaction at inflation pressures of 180, 207 and 235 kPa as these were overshadowed by the effect of the initial soil strength. However, it would not be advisable to operate at 180 kPa when carrying the present payloads as the tyres would run flat.

3 Within a moisture content of 17 and 21% (wet weight) the present single bundle trailers do not cause significant soil compaction. There are however, 45 and 72% chances that nucleus estate trailers induce significant compaction in upland and lowland fields respectively. There are some chances that the high capacity bin trailer causes significant soil compaction in lowland fields.

7.3. Recommendations

1. To avoid hardpan formation the ploughing depth should be increased from 25.4 to 30 cm. It should be noted that this increase will increase the cost of ploughing because of the increased draft. Consequently fuel consumption will also rise.

2. The current average inflation pressure of 207 kPa (30 psi) used in 18.4x30, 10 ply tyres is adequate. However, when the values established from this research are adopted, tyre

specification manuals like the one established by Traux et al. (1985) must be used to select the appropriate tyre pressures.

3. To increase the tonnage delivered by the present single bundle trailers (SBT) the payloads carried should on average be 7300 kg. To carry beyond 7300 kg up to the established safe payload of 9000 kg a new SBT design will be required.
4. Nucleus estate trailers should be loaded to payloads of 7630 kg in upland fields and 6770 kg in lowland fields for moisture contents of 17 to 21% (wet weight) to avoid significant soil compaction.
5. From the research findings it is advisable to stick to an 18.4x30 tyre on all single and high capacity bin trailers. However, in order to continue carrying the present amount of sugarcane on nucleus estate trailers, wider tyres will be required. This is because use of wider tyres than 18.4x30 will reduce ground contact pressures. This in turn will reduce the induced soil compaction.
6. A study relating levels of soil compaction and sugarcane yield loss will be useful. This study should isolate soil compaction effects on yields from other factors that affect yields such as cane treading by machinery, diseases, weather, sugarcane variety, soil fertility, alkalinity and

acidity and drainage.

7. There is need to establish critical soil compaction levels for the soils of Mumias. This may be achieved by studying the behaviour of sugarcane roots as they develop in soils compacted to various bulk densities.
8. Investigations into the possibility of increasing the density of sugarcane stacks carried by the present single bundle trailers are necessary.
9. A study should be conducted on NETs to find out whether weight transfer or the build materials are a cause to the high axle loads they induce over SBTs while carrying similar payloads.
10. Good machinery management may be achieved if one is able to predict the level of soil compaction that may be induced given values of axle loads, soil type and moisture contents. Use of precipitation rather than soil moisture content in the prediction of soil compaction levels would be faster. A study to relate precipitation to field moisture content would therefore be of profound importance to soil compaction studies and field machinery management as well.

8. APPENDICES

APPENDIX 1

The soils of Mumias

Appendix 1 shows the soil characteristics of Mumias Sugar Zone. The area has been divided into eleven soil units. Main soil features in each unit, soil limitations, drainage limitations, suitability for sugarcane growing and management requirements are shown.

Source: Booker Agriculture International Limited (1969).

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Table A1. Soil characteristics of Mumias sugar zone

Soil Unit	Main Features	Soil Limitations	Drainage Limitations	Suitability for sugarcane	Management Requirements
1	Red to brown sandy clay loam surface over clay or sandy clay subsoils, at least 180 cm deep, free of stones and gravel; surface pH 4.5 to 5.5, occurs on ridge crests and upper slopes, 0 to 2 degrees.	Low levels of plant nutrients	None	very suitable	Ploughing, harrowing and fertilizer application
2	Red to brown sandy clay loam surface over sandy clay or clay subsoils, top 90 cm stone and gravel free, surface pH 5.0 to 6.0, occurs on ridge crests and upper slope, 0 to 2 degrees	Low levels of plant nutrients, rock and/or plinthite fragments below 90 cm	None	Suitable	Ploughing, harrowing and fertilizer application
3	Dark medium to fine textured surface over coarse textured centre overlying strongly glazed clay or sandy clay, gravels sometimes present in subsoil, surface pH 5.0 to 5.5 lower slopes (0.5 to 5 deg.), above, at and below spring lines	very low levels of plant nutrients. Low permeability of glazed subsoil	Poorly drained	Suitable if properly drained	Cut-off drains, surface and in-field drains, some land forming, possibly limited subsoil cultivation. Ploughing, harrowing, ridging and fertilizer application
5	Dark sandy or silty clay loam over strongly glazed clay or silty clay, often an horizon with much plinthite gravel, surface pH 5.0 to 6.0 flat (0 to 2 deg.) valley floors	Low plant nutrient levels, low permeability	Very poorly drained, standing surface water for some months	Suitable if effectively drained	Surface and in-field drains, forming, probably subsoil cultivation and/or mole draining. Ploughing, harrowing, ridging and fertilizing
6	As unit 2 above, but with much rock or plinthite in top 90 cm, shallow soils, slopes greater than 2 degrees	Low nutrient and water holding levels	None	Unsuitable	
8	Rock outcrops or massive petroplinthite	Very shallow or no soil	None	Unsuitable	
[illegible]	Developed or occupied sites, e.g. townships, schools, Pan-African Paper Mill, Webuye				

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APPENDIX 2

Criteria used in selection of critical bulk density for the soils of Mumias

In this appendix the argument following the choice of Ferralic CAMBISOLS (Low Humic Latosols) as representative soils in the nucleus estate of Mumias Sugar Company is given. The soils described here have been obtained from the Kenya Soil Survey Map of 1982, Mumias area. This soil map covers a small section of the nucleus estate of Mumias Sugar Company.

Table A2. Soils found around the Nucleus Estate of Mumias Sugar Company

Legend from map and parts covered	Soil description
1. UG_3M/AB Nucleus Estate	These are soils developed on acid rocks (granite). They are found in the uplands . They are shallow and well drained. They are moderately deep dark reddish brown to strong brown, friable clay, over petroplinthite, marrum (Ferralic CAMBISOLS petroferric phase and orthic Ferralsols, petroferric phase).
2. V_rc_1/BC Along River Nzoia.	These are soils developed on various parent materials. They are complexes of excessively drained to well drained, deep yellowish brown to grey, loose loamy sand to sandy loam (Ferralic ARENOSOLS) and imperfectly drained to poorly drained, deep dark brown to dark greyish brown, mottled, firm, sandy clay to clay (eutri Gleysols).
3. UGb_1/B Factory and parts of the Nucleus Estate	Soils developed on acid igneous rocks (granite). They are found in the uplands. They are well drained, deep to very deep, yellowish brown, friable to firm, sandy clay to clay (orthic ACRISOLS and plinthic FERRALSOLS).

Table A2 shows that the soils in the three parts considered have Ferralic properties. Buringh (1979) classifies Ferralic CAMBISOLS as Low Humic Latosols. Ferralic CAMBISOLS are Cambisols with ferralic properties. Ferralic properties are properties of soils that are almost Ferralsols, but the texture is too coarse and therefore are classified as a Ferralic group in the Cambisols and Arenosols. The soils in sections UG_3M/AB, V_rc_1/BC and UGb_1/B all have the ferralic properties. The classification of the soils in the nucleus estate of Mumias Sugar Company as Low Humic Latosols is therefore a close description of this soils. The properties of Low Humic Latosols especially the critical bulk density for the growth of sugarcane can therefore be used in the analysis.

Hydrol Humic Latosols (Humic ANDOSOLS) on the other hand do not show ferralic properties. These soils often occur in cool and humic regions, in the tropics at altitudes of some hundred metres or more. They are therefore not characteristic of the soil of Mumias.

Gray Hydromorphic Clay are clay soils with hydromorphic properties. Soil textural analysis (Tables 5.5 and 5.6) indicate that even the lowland fields of Mumias have a high proportion of sand.

APPENDIX 3

Test Vehicle Calibration

Appendix 3 describes the procedure used in the calibration of the test vehicle. Graphical relationships between axle load and water level in the test vehicle were established. During the test one merely made a water level reading and with the help of the calibration results the corresponding axle load was determined.

Procedure

The water bowser was calibrated before it was used. Conversion graphs developed are shown in Figure A3.

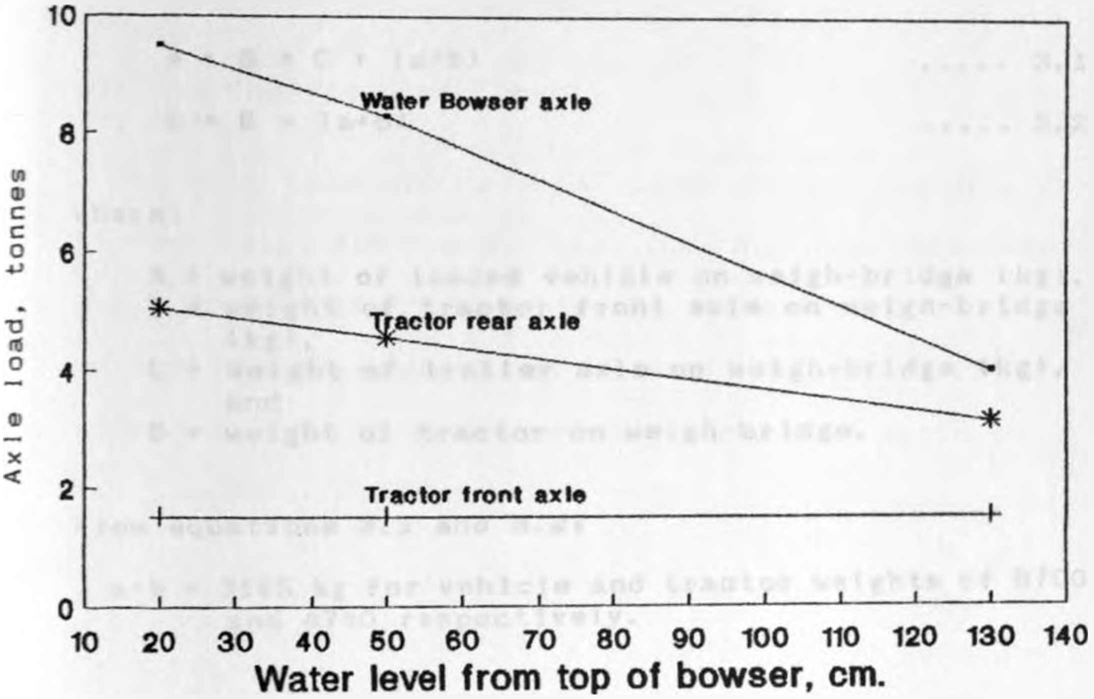


Fig.A3. Water level to axle load conversion graph.

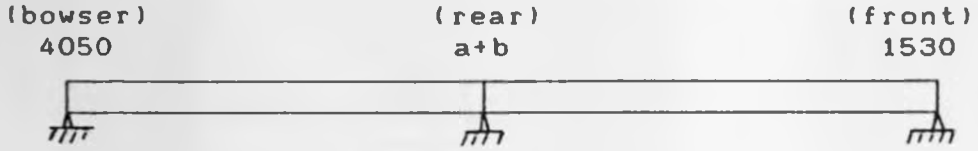
To develop these graphs weigh-bridge measurements shown in Table A3 were used.

Table A3. Weigh-bridge readings used to calibrate the Test Vehicle

W-level bowser,	Tractor on w/b (kg)	Vehicle on w/b (kg)	Bowser on w/b (kg)	T-front on w/b (kg)
130	4740	8700	4050	1530
50	6150	14360	8300	1530
20	6650	16000	9480	1530

W-level = water level (cm),
w/b = weigh-bridge and
T-front = tractor front axle.

Tractor rear axle load was computed as follows:



$A = B + C + (a+b)$ 3.1

$D = B + (a+b)$ 3.2

where:

A = weight of loaded vehicle on weigh-bridge (kg),
B = weight of tractor front axle on weigh-bridge (kg),
C = weight of trailer axle on weigh-bridge (kg), and
D = weight of tractor on weigh-bridge.

From equations 3.1 and 3.2:

a+b = 3165 kg for vehicle and tractor weights of 8700 and 4740 respectively.

APPENDIX 4

Detailed Experimental Layout

In this appendix detailed experimental layouts at the test sites are shown. Axle load application varied from 0 to 9 tonnes. Three levels of moisture content and tyre pressure were used at each experimental site. Sites A18x and B3 each measures 67.5x15 m while site D118x measures 30x15 m.

Moisture (%)	21.3														
T. Press (kPa)	207					180					235				
Axle load (ton)	9	8	7	5	0	0	5	9	7	8	5	0	9	7	8
	x o x o x														

Moisture (%)	17.2															22.1									
T. Press (kPa)	180					235					207					207					180				
Axle load (ton)	9	8	7	0	5	9	0	8	7	5	5	0	7	9	8	9	5	8	0	7	9	7	0	8	5

Moisture (%)	22.1				
T. Press (kPa)	235				
Axle load (ton)	7	8	9	5	0

Experimental layout for Site A18x

Moisture (%)	18.3														
T. Press (kPa)	235					180					207				
Axle load (ton)	9	8	7	5	0	0	7	9	5	8	5	7	0	9	8
	x o x o x														

Experimental layout for site B3.

T.Press = tyre pressure,
x = bulk density samples taken from here, and
o = penetrometer readings taken from here.

20.8															20.9										20.9				
180					235					207					207					235					180				
7	0	9	5	8	9	8	7	5	0	0	8	7	9	5	0	7	9	5	8	0	9	5	8	7	5	0	8	9	7

Experimental layout for Site B3 (Cont'd).

Moisture (%)	22.4										24.4					24.4				
T. Press (kPa)	235					207					207					235				
Axle load (ton)	9	5	8	0	7	9	8	7	0	5	9	0	5	8	7	0	7	8	5	9
	x o x o x																			

Experimental layout for site D118x.

T.Press = tyre pressure,
x = bulk density samples taken from here, and
o = penetrometer readings taken from here.

APPENDIX 5

The establishment of the formula used in calculation of the tyre contact area

Appendix 5 shows the procedure used in the establishment of the formula used in the calculation of the tyre area of contact. The relation between the area, length and width of a few randomly chosen elliptical tyre prints is given.

Procedure

The ellipses used were chosen at random in the course of the tests. Print length and width were measured. The actual area of the ellipse was obtained by square count. To calculate the area of the other ellipses whose dimensions were the only measured parameters, an estimate of the area was obtained from:

$$\text{Area} = b\ LW \qquad \ldots\ldots\ 5.1$$

where:

b = a regression coefficient,
L, W = the largest length and width of the ellipse respectively (cm).

The data used is shown in Table A5. The regression coefficient obtained was 0.886 with a correlation factor of 0.988. The area of contact was estimated by:

$$\text{Area} = 0.886\ LW \qquad \ldots\ldots\ 5.2$$

Table A5. Print area values

Area by square count (cm^2)	Ellipse (cm) Length	Width	LxW
2600	65	44	2860
2325	66	41	2706
2225	63	38	2394
2550	70	42	2940
2300	67	40	2680
2600	72	41	2952
2550	68	43	2924
2700	69	43	2967
2400	69	40	2760
2150	64	39	2496
2200	67	41	2747
2650	69	42	2898
2400	68	42	2856
2950	74	45	3330
2400	60	43	2580
2550	61	45	2745
2625	64	45	2880
2750	67	45	3015

APPENDIX 6

Standard Proctor Test Procedure

In order to develop relations between soil compaction, soil moisture and the compacting effort a procedure similar to the standard Proctor Test was used. This appendix describes the Standard Proctor Test as described by Bowles (1978).

Procedure

Note: A water-content sample should be taken 24h prior to this test so that the initial water content can be reasonably estimated; otherwise it may take 6 to 8 trials to obtain the compaction curve-especially for any soils where OMC is 17 to 22 percent.

1. Take 3 kg (nominal weight) of air-dry soil, pulverize sufficiently to run through the No.4 sieve, then mix with the initial percentage of water based on estimated dry weight. The initial percentage of water should be based on the present water content, a desired initial moisture content 4 to 5 percent below OMC, and obtain OMC from Fig.A6.1 or other means of estimation.

The soil and water should be premixed and cured for about 24h prior to the test.

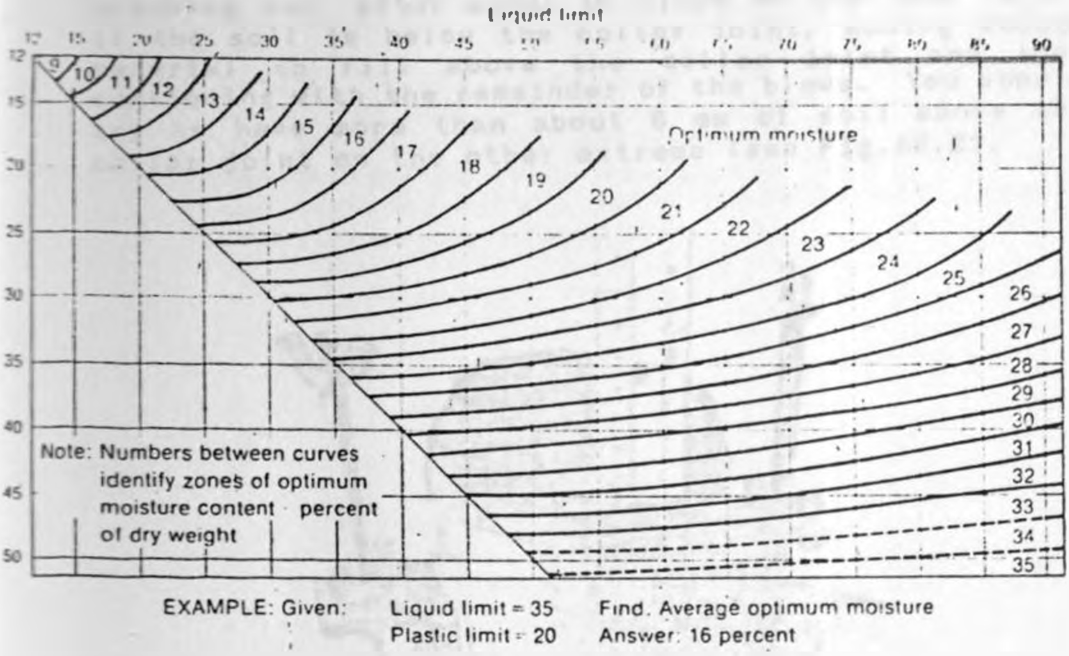


Fig. A6.1. Chart to find the approximate optimum moisture content (OMC) of a soil in the standard compaction test.

2. If the soil has been "cured," add 1 percent moisture by weight [.01x3 = 0.03 kg (30 ml)] to account for evaporation losses. Mix this water into the soil carefully.

3. Weigh the compaction mould but do not include collar or base plate.
4. Measure the compaction mould to determine its volume.
5. Use either the standard or modified compaction method as specified by the instructor and compact a cylinder of soil. If you use a 1000 c.c. mould, use 26 blows per layer instead of 25 to produce the same compaction energy and for either test.
6. Carefully strike both the top and base of the compaction cylinder of soil with a steel straight-edge. Fill in any holes in the compaction specimen with either soil or gravel which is smaller than the hole where the smoothing process removes any pebbles or soil.

Note. If the mould is not filled above the collar joint from the last compacted layer, do not add soil to make up the deficiency-redo the test. You can avoid this unpleasant situation, however, by carefully watching and, after about 10 blows on the last layer, if the soil is below the collar joint, adding enough material to fill above the collar joint and then continuing with the remainder of the blows. You should try to have more than about 6 mm of soil above the collar joint on the other extreme (see Fig.A6.2).

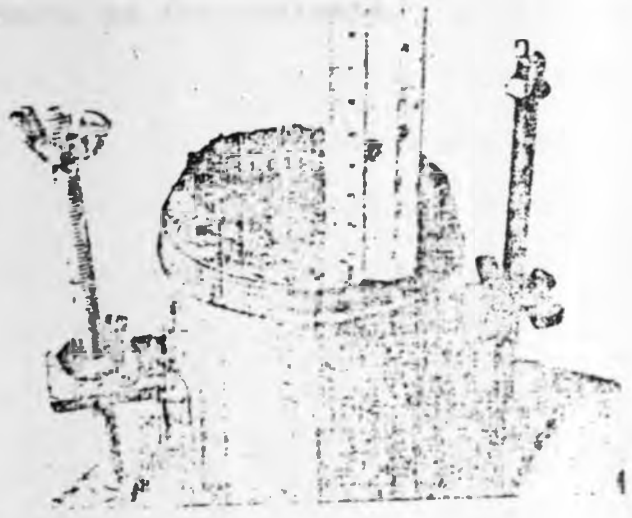


Fig.A6.2. Compacted soil specimen with collar removed and initial trimming. Note that soil projects only about 6 mm above mould.

If you have much more than this amount of excess and are not careful, you will remove the last layer of compacted soil cake when you remove the collar. If you do this, redo the test since you can never replace the soil cake properly. If the collar is hard to remove, do not risk twisting off the third (or last) layer of soil; take a spatula and trim along the sides of the collar until it comes of easily. Remember that you have an error multiplier of 1060 in this project; therefore,an error of 15 g of soil is about 0.15 kN/m^3 of compaction error-and 15 g of soil is not a very large quantity.

7. Weigh the mould and cylinder of soil.
8. Extrude the cylinder of soil from the mould, split it, and take two water-content samples-one near the top and the other near the bottom-of as much as the moisture cups will hold (about 100 g).
9. Break the sample to (-) No.4 sieve size and add 2 percent (based on the original sample weight of 3 kg) of water. Carefully remix and repeat steps 5 to 9 until, based on wet weights, a peak value is followed by two slightly lesser compacted weights.
10. Return to the laboratory the following day and weigh the oven-dry water-content samples to find the actual average water content of each test.
11. Compute the dry unit weight and make a plot of dry bulk density versus water content, with dry bulk density as the ordinate.

APPENDIX 7

Calculation to support choice of four passes in the Proctor Test

In this appendix a calculation is made showing the reason for simulating four passes in the Proctor Test. During the field test, the test vehicle made two passes on any treated section. Therefore the trailer, tractor rear and front wheels each made two passes on any treated section. It is shown that the sum of the ground contact pressures developed by the tractor front and rear wheels was approximately equal to that for the trailer wheel. When the tractor front and rear wheels made two passes, their influence was therefore assumed to be equal to two trailer wheel passes. In effect, for two vehicle passes an equivalent of four trailer wheel passes are made.

Table A7. Area of contact for the rear and front of a tractor, and water bowser tyres at various axle loads

Axle load, kg			Contact area, cm^2		
b-tyre	t-rear	t-front	b-tyre	t-rear	t-front
7610	4290	1460	3841	2150	1162.5
6880	4000	1460	3095	2150	1112.5
6240	3750	1460	3290	2225	1112.5
3890	3400	1460	4110	2055	1162.5

Where:
b-tyre = bowser tyre,
t-rear = tractor rear tyre and
t-front = tractor front tyre.

Table A7 shows some contact area values obtained in the preliminary tests for the research. It seems that area of contact for tractor front and rear tyres did not vary significantly as the axle load was increased. This could be due to:

(i) the tractor tyres sunk deeper as the load was increased,
(ii) the tyres did not deform as the load was increased,
(iii) the method of measuring contact area was not sensitive enough to detect any small differences in the values obtained.
(iv) a horizontal plane was used as the area of contact neglecting the contribution made by the side walls of the tyre.

The area of contact of the tractor front and rear tyres can be estimated by the mean of the values in Table A7. Using Figure A3 maximum ground contact pressures developed by the tyres are:

Tractor front = 7.5/0.11375
66.0 kPa (9.55 psi)

Tractor rear = 24.5/0.21375
114.6 kPa (16.6 psi)

The water bowser tyres developed a ground contact pressure of about 169 kPa (24.5 psi). Hence the sum of the pressures developed by both the tractor rear and front tyres is approximately equal to that developed by the water bowser tyre.

APPENDIX 8

Calibration of the Penetrometer

Appendix 8 shows the procedure for the calibration of the penetrometer used during the field tests. To be able to convert the penetrometer dial readings to kilogrammes, a regression relationship between the dial readings and balance readings (kg) was established. During the field tests one merely made penetrometer readings.

The penetrometer was calibrated before it was used. Table A8 shows the values that were used to convert penetrometer dial readings into kilogrammes.

Table A8. Penetrometer dial reading conversion

Penetrometer dial reading CI	Balance reading (kg)	Regression output	
10	1.6	Constant	0
20	3.6	Std Err of kg Est	0.641
30	5.4	R squared	0.998
40	7.8	No of Observations	15
50	10.2	Degrees of Freedom	14
60	13.4	CI Coefficient(s)	0.220
70	14.6	Std Err of Coef	0.0016
80	17.6		
90	20.0		
100	21.8		
120	27.0		
140	30.6		
160	35.2		
180	40.0		
200	44.6		

Equation 8 developed was used to convert penetrometer dial readings to kilogrammes.

$$P = 0.2203\ b \qquad \ldots\ldots\ 8$$

where:

P = reading in kg and
b = penetrometer dial reading.

APPENDIX 9

Weigh-bridge readings for SBTs and NETs.

Appendix 9 shows weigh-bridge readings collected for Single Bundle (SBT) and Nucleus Estate (NET) Trailers. The mean of the empty trailer axle loads was computed. The appendix also shows the procedure used in the establishment of the relationship between the developed trailer axle loads and payloads carried by SBTs and NETs.

Table A9.1. Weigh-bridge readings for Single Bundle Trailers

Serial number	Reg. No	Weight of loaded vehicle in kg.	Payload (kg)	Axle load, kg (loaded trailer)	Axle load, kg (empty trailer)
1	CT263	11500	5600	5680	2110
2	CT270	11180	5360	5320	2000
3	CT269	12210	6420	5870	2030
4	CT1479	13730	8000	6670	2020
5	CT350	12890	6850	7040	2260
6	CT1475	13020	7330	6110	1940
7	CT269	13550	7800	6410	2050
8	CT346	10830	4860	5070	2220
9	CT505	13590	7680	6620	
10	CT469	12730	6730	6130	2130
11	CT1458	13180	7280	6300	2020
12	CT1460	10830	4960	4950	2060
13	CT1480	13880	7990	6410	2100
14	CT503	14060	8120	6650	2160
15	CT267	13930	7960	6210	2230
16	CT247	11520	5580	5580	2180
17	CT262	12780	6850	6380	2200
18	CT518	12300	6540	6020	2180
19	CT496	11980	5810	5680	2310
20	CT352	13960	7990	6800	2270
				Mean	2130

Source: Tyre specification in relation to in-field cane transport, 1985.

Table A9.2. Weigh-bridge readings for Nucleus Estate Trailers

Serial number	Reg. No	Weight of loaded vehicle in kg.	Payload (kg)	Axle load, kg (loaded trailer)	Axle load, kg (empty trailer)
1	CT282	13750.00	6670.00	7260.00	2640.00
2	CT285	13390.00	6480.00	7110.00	2560.00
3	CT285	12730.00	6020.00	6550.00	2520.00
4	CT282	12970.00	6030.00	6900.00	
5	CT280	13900.00	7040.00	7690.00	2580.00
6	CT281	12640.00	5840.00	6600.00	2600.00
7	CT298	13640.00	6540.00	7260.00	2630.00
8	CT276	13280.00	6530.00	7190.00	2560.00
9	CT273	13030.00	6070.00	7020.00	2680.00
10	CT280	11840.00	4850.00	6230.00	2620.00
11	CT282	14650.00	7160.00	8150.00	2900.00
12	CT274	16060.00	8890.00	9160.00	2830.00
13	CT285	16140.00	9080.00	9100.00	2790.00
14	CT280	15000.00	7800.00	8460.00	2910.00
15	CT285	14000.00	7030.00	7580.00	2750.00
16	CT299	15540.00	8230.00	8940.00	3000.00
17	CT281	15450.00	8400.00	8610.00	2790.00
18	CT285	15050.00	8080.00	8530.00	2800.00
19	CT299	16220.00	8920.00	9420.00	2980.00
20	CT299	15610.00	8300.00	8680.00	2950.00
				Mean	2741.58

Source: Tyre specification in relation to in-field cane transport, 1985.

Table A9.3. Establishing values of m and c in the equation: $Y = mX + c$ for single bundle trailers.

Serial number	Payload (kg)	Axle load, kg (loaded trailer)	m 0.6	Payload (kg)	Axle load, kg (loaded trailer)	m 0.599	Differences 0.6	Differences 0.599
1	6420	6530	6002	6420	6530	5995.58	-528	-534.42
2	5110	5260	5216	5110	5260	5210.89	-44	-49.11
3	5610	5100	5516	5610	5100	5510.39	416	410.39
4	6240	5850	5894	6240	5850	5887.76	44	37.76
5	6640	6200	6134	6640	6200	6127.36	-66	-72.64
6	7350	6300	6560	7350	6300	6552.65	260	252.65
7	5390	5260	5384	5390	5260	5378.61	124	118.61
8	6220	5950	5882	6220	5950	5875.78	-68	-74.22
9	6010	5450	5756	6010	5450	5749.99	306	299.99
10	6660	5920	6146	6660	5920	6139.34	226	219.34
11	5420	5620	5402	5420	5620	5396.58	-218	-223.42
12	5470	5200	5432	5470	5200	5426.53	232	226.53
13	5200	5320	5270	5200	5320	5264.8	-50	-55.2
14	4340	4660	4754	4340	4660	4749.66	94	89.66
15	6150	5790	5840	6150	5790	5833.85	50	43.85
16	4170	5350	4652	4170	5350	4647.83	-698	-702.17
17	4430	4630	4808	4430	4630	4803.57	178	173.57
18	6300	5950	5930	6300	5950	5923.7	-20	-26.3
19	8180	7350	7058	8180	7350	7049.82	-292	-300.18
20	8110	7350	7016	8110	7350	7007.89	-334	-342.11
21	4190	4900	4664	4190	4900	4659.81	-236	-240.19
22	5620	5780	5522	5620	5780	5516.38	-258	-263.62
23	5430	5390	5408	5430	5390	5402.57	18	12.57
24	5280	4950	5318	5280	4950	5312.72	368	362.72
25	6190	5720	5864	6190	5720	5857.81	144	137.81
26	5440	6100	5414	5440	6100	5408.56	-686	-691.44
27	5360	5380	5366	5360	5380	5360.64	-14	-19.36
28	6690	6650	6164	6690	6650	6157.31	-486	-492.69
29	5790	6280	5624	5790	6280	5618.21	-656	-661.79
30	6170	5700	5852	6170	5700	5845.83	152	145.83
31	6470	6090	6032	6470	6090	6025.53	-58	-64.47
32	6230	6280	5888	6230	6280	5881.77	-392	-398.23
33	4790	4810	5024	4790	4810	5019.21	214	209.21
34	5600	5680	5510	5600	5680	5504.4	-170	-175.6
35	5360	5320	5366	5360	5320	5360.64	46	40.64
36	6420	5870	6002	6420	5870	5995.58	132	125.58
37	8000	6670	6950	8000	6670	6942	280	272
38	6850	7040	6260	6850	7040	6253.15	-780	-786.85
39	7330	6110	6548	7330	6110	6540.67	438	430.67

Table A9.3. (Cont'd)

Serial number	Payload (kg)	Axle load, kg (loaded trailer)	m 0.6	Payload (kg)	Axle load, kg (loaded trailer)	m 0.599	Differences 0.6	Differences 0.599
40	7800	6410	6830	7800	6410	6822.2	420	412.2
41	4860	5070	5066	4860	5070	5061.14	-4	-8.86
42	7680	6620	6758	7680	6620	6750.32	138	130.32
43	6730	6130	6188	6730	6130	6181.27	58	51.27
44	7280	6300	6518	7280	6300	6510.72	218	210.72
45	4960	4950	5126	4960	4950	5121.04	176	171.04
46	7990	6410	6944	7990	6410	6936.01	534	526.01
47	8120	6650	7022	8120	6650	7013.88	372	363.88
48	7960	6210	6926	7960	6210	6918.04	716	708.04
49	5580	5580	5498	5580	5580	5492.42	-82	-87.58
50	6850	6380	6260	6850	6380	6253.15	-120	-126.85
51	6540	6020	6074	6540	6020	6067.46	54	47.46
52	5810	5680	5636	5810	5680	5630.19	-44	-49.81
53	7990	6800	6944	7990	6800	6936.01	144	136.01
		2150			2150		248.6	-80.181

In this table: Y = axle load; X = payload in kg. Mean empty trailer axle load = 2150 kg.

Table A9.4. Establishing values of m and c in the equation: Y = mX + c for Nucleus Estate Trailers

Serial number	Serial number	Axle load, kg (loaded trailer)	Payload (kg)	m 0.713	Axle load, kg (loaded trailer)	Payload (kg)	m 0.713	0.713	differences 0.713
1	1	6950.000	6320.000	7223.000	6950.000	6320.000	7223.632	273.000	273.632
2	2	6930.000	6090.000	7059.125	6930.000	6090.000	7059.734	129.125	129.734
3	3	8960.000	8650.000	8883.125	8960.000	8650.000	8883.990	-76.875	-76.010
4	4	8180.000	7900.000	8348.750	8180.000	7900.000	8349.540	168.750	169.540
5	5	8560.000	8340.000	8662.250	8560.000	8340.000	8663.084	102.250	103.084
6	6	7310.000	6720.000	7508.000	7310.000	6720.000	7508.672	198.000	198.672
7	7	7370.000	6540.000	7379.750	7370.000	6540.000	7380.404	9.750	10.404
8	8	7700.000	7200.000	7850.000	7700.000	7200.000	7850.720	150.000	150.720
9	9	8720.000	7270.000	7899.875	8720.000	7270.000	7900.602	-820.125	-819.398
10	10	5490.000	5485.000	6628.063	5490.000	5485.000	6628.611	1138.063	1138.611
11	11	8220.000	7800.000	8277.500	8220.000	7800.000	8278.280	57.500	58.280
12	12	9320.000	9260.000	9317.750	9320.000	9260.000	9318.676	-2.250	-1.324
13	13	7550.000	6750.000	7529.375	7550.000	6750.000	7530.050	-20.625	-19.950
14	14	6830.000	5680.000	6767.000	6830.000	5680.000	6767.568	-63.000	-62.432
15	15	8200.000	7300.000	7921.250	8200.000	7300.000	7921.980	-278.750	-278.020
16	16	8950.000	8750.000	8954.375	8950.000	8750.000	8955.250	4.375	5.250
17	17	8050.000	6760.000	7536.500	8050.000	6760.000	7537.176	-513.500	-512.824
18	18	8630.000	8400.000	8705.000	8630.000	8400.000	8705.840	75.000	75.840
19	19	7820.000	7230.000	7871.375	7820.000	7230.000	7872.098	51.375	52.098
20	20	8410.000	8020.000	8434.250	8410.000	8020.000	8435.052	24.250	25.052
21	21	8730.000	8580.000	8833.250	8730.000	8580.000	8834.108	103.250	104.108
22	22	7910.000	6280.000	7194.500	7910.000	6280.000	7195.128	-715.500	-714.872
23	23	7610.000	7240.000	7878.500	7610.000	7240.000	7879.224	268.500	269.224
24	24	8830.000	8650.000	8883.125	8830.000	8650.000	8883.990	53.125	53.990
25	25	7500.000	6670.000	7472.375	7500.000	6670.000	7473.042	-27.625	-26.958
26	26	7850.000	7400.000	7992.500	7850.000	7400.000	7993.240	142.500	143.240
27	27	8880.000	8010.000	8427.125	8880.000	8010.000	8427.926	-452.875	-452.074
28	28	7690.000	7080.000	7764.500	7690.000	7080.000	7765.208	74.500	75.208
29	29	8900.000	8580.000	8833.250	8900.000	8580.000	8834.108	-66.750	-65.892
30	30	8020.000	7690.000	8199.125	8020.000	7690.000	8199.894	179.125	179.894
31	31	7900.000	7670.000	8184.875	7900.000	7670.000	8185.642	284.875	285.642
32	32	8340.000	8110.000	8498.375	8340.000	8110.000	8499.186	158.375	159.186
33	33	8390.000	7900.000	8348.750	8390.000	7900.000	8349.540	-41.250	-40.460
34	34	8580.000	8160.000	8534.000	8580.000	8160.000	8534.816	-46.000	-45.184
35	35	7820.000	7350.000	7956.875	7820.000	7350.000	7957.610	136.875	137.610
36	36	8390.000	7990.000	8412.875	8390.000	7990.000	8413.674	22.875	23.674
37	37	8810.000	8470.000	8754.875	8810.000	8470.000	8755.722	-55.125	-54.278
38	38	8150.000	6920.000	7650.500	8150.000	6920.000	7651.192	-499.500	-498.808
39	39	7840.000	7230.000	7871.375	7840.000	7230.000	7872.098	31.375	32.098
40	40	7870.000	6240.000	7166.000	7870.000	6240.000	7166.624	-704.000	-703.376

Table A9.4. (Cont'd)

Serial number	Serial number	Axle load, kg (loaded trailer)	Payload (kg)	m 0.713	Axle load, kg (loaded trailer)	Payload (kg)	m 0.713	0.713	differences 0.713
41	41	7260.000	6670.000	7472.375	7260.000	6670.000	7473.042	212.375	213.042
42	42	7110.000	6480.000	7337.000	7110.000	6480.000	7337.648	227.000	227.648
43	43	6550.000	6020.000	7009.250	6550.000	6020.000	7009.852	459.250	459.852
44	44	6900.000	6030.000	7016.375	6900.000	6030.000	7016.978	116.375	116.978
45	45	7690.000	7040.000	7736.000	7690.000	7040.000	7736.704	46.000	46.704
46	46	6600.000	5840.000	6881.000	6600.000	5840.000	6881.584	281.000	281.584
47	47	7260.000	6540.000	7379.750	7260.000	6540.000	7380.404	119.750	120.404
48	48	7190.000	6530.000	7372.625	7190.000	6530.000	7373.278	182.625	183.278
49	49	7020.000	6070.000	7044.875	7020.000	6070.000	7045.482	24.875	25.482
50	50	6230.000	4850.000	6175.625	6230.000	4850.000	6176.110	-54.375	-53.890
51	51	8150.000	7160.000	7821.500	8150.000	7160.000	7822.216	-328.500	-327.784
52	52	9160.000	8890.000	9054.125	9160.000	8890.000	9055.014	-105.875	-104.986
53	53	9100.000	9080.000	9189.500	9100.000	9080.000	9190.408	89.500	90.408
54	54	8460.000	7800.000	8277.500	8460.000	7800.000	8278.280	-182.500	-181.720
55	55	7580.000	7030.000	7728.875	7580.000	7030.000	7729.578	148.875	149.578
56	56	8940.000	8230.000	8583.875	8940.000	8230.000	8584.698	-356.125	-355.302
57	57	8610.000	8400.000	8705.000	8610.000	8400.000	8705.840	95.000	95.840
58	58	8530.000	8080.000	8477.000	8530.000	8080.000	8477.808	-53.000	-52.192
59	59	9420.000	8920.000	9075.500	9420.000	8920.000	9076.392	-344.500	-343.608
60	60	8680.000	8300.000	8633.750	8680.000	8300.000	8634.580	-46.250	-45.420
			2720.000			2720.000		-14.725	29.540

In this tIn this table: Y = axle load; X = payload in kg. c = 2720 kg (mean empty trailer axle load).

9. REFERENCES

Anonymous, 1985. Tyre specification in relation to infield cane transport. Section Paper No. 21 Mumias, unpublished.

Andrews, L.A. and W.M. Broadfoot, 1958. The San Dimas soil core sampler. Soil Science 85(6): 297-301.

Ayers, P.D. and J.V. Perumpral, 1982. Moisture and density effect on cone index. Transaction of the American Society of Agricultural Engineers 25(5): 1169-1172.

Barnes, K.K., W.M. Carleton, H.M. Taylor, G.E. Vanden Berg and R.I. Throckmorton, 1971. Compaction of agricultural soils. St. Joseph, Michigan, An American Society of Agricultural Engineers Monograph.

Bashford, L.L., A.J. Jones and L.N. Mielke, 1987. Bulk density beneath a belt track and an agricultural tractor. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper No 871054).

Bekker, M.G., 1957. Theory of land locomotion. Ann Arbor, Michigan.

Booker Agriculture International Limited, 1969. Feasibility study report for Mumias. London, Great Britain.

Bowles, J.E., 1978. Engineering properties of soils and their measurement. New York, McGraw-Hill Book Company: pp 84-88.

Brandon, J.R and J.V. Perumpral, 1986. Constitutive relationships for agricultural soils. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper No. 861052).

Brandon, J.R., T. Kuppusamy and J.V. Perumpral, 1987. Stress-strain model for agricultural soils. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper No. 8710552).

Burger, J.A., J.V. Perumpral, R.E. Kreh, J.L. Torbet and S. Minaci, 1983. The effect of track and rubber tyred vehicles on soil compaction. American Society of Agricultural Engineers Paper No. 83: 1621, St. Joseph, Michigan 49085.

Buringh, P., 1979. Introduction to the study of soils in tropical and subtropical regions. Wageningen, Centre for Agricultural Publishing and Documentation.

Chesness, J.L., E.E. Ruiz and C. Cobb, 1972. Quantitative description of soil compaction in peach orchads utilising a portable penetrometer. St. Joseph, Michigan, Transactions of the American Society of Agricutlural Engineers 15(2): 217-219.

Dexter, A.R., R. Horn, R. Holloway and B.F. Jakobsen, 1988. Pressure transmission beneath wheels in soils on the Eyre Peninsula of South Australia. London, Journal of Terramechanics (Volume 25, number 2:135-147), Perganon Press Plc.

Dias, A and S. Nortcliff, 1984. Effects of tractor passes on the physical properties of an Oxisol in the Brazilian Amazon. University of Reading, Department of Soil Science.

Drew, D.P., 1972. Sugarcane transport trials at Mumias. London, Booker Agrculture International Ltd.

Ellwein, P.G and D.P. Froehlich, 1989. Relationships between parameters of combine design and soil compaction. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 891091).

Erbach, D., 1987. Measurement of soil bulk density and moisture content. St. Joseph, Michigan, Transaction of American Society of Agricultural Engineers (Vol.30 pp 922-931).

Foale, M.A. and D.R. Upchurch, 1982. Soil coring method for sites with restricted access. Agronomy Journal 74: 761-763.

Froelich, O.K., 1934. Pressure distribution in the soil. Wien, Austria.

Gameda, S., G.S. Raghavan and E. Mckyes, 1989. Correlations between constitutive properties and soil parameters. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 891099).

Gerard, C.J., C.A. Burleson, W.R. Cowley, M.E. Bloodworth and G.W. Kunze, 1964. Hardpan formation in coarse and medium textured soils in the lower Rio Grande valley of Texas. B1007, Texas A and M University.

Gunjal, K., G. Lavoie and G.S.V. Raghavan, 1987. Economics of soil compaction due to machinery traffic and implications for machinery selection. McGill University, Canadian Journal of Agricultural Economics, Vol. 35 pp. 591-603.

Hakansson, I. and D. Birger, 1981. Effects of heavy traffic on soil conditions and growth. 7th. Production of the International Conference of ISTVS, Calgary, Alberta, Canada, Vol. 1, pp. 239-53.

Hegedus, E., 1958. Effect of water content on "B3-Values" of soil. Report No. 27, Land Locomotion Laboratory, Warren, Michigan.

Hovanesian, J.D., 1958. Development and use of a volumetric transducer for studies of parameters upon soil compaction. Ph.D Thesis, Michigan State University, East Lansing.

Humbert, R.P., 1968. The growing of sugarcane. Elsevier Publishing Company, Amsterdam.

International Soil Tillage Research Laboratory, 1981. Soil tillage research, Volume 1, pages 207-232, 373-397. Amsterdam, Elsevier Publishing Company.

International Soil Tillage Research Laboratory, 1982. Soil tillage research, Vol. 2: 3-36. Amsterdam, Elsevier Publishing Company.

Kamau, J.N. 1988. Soil compaction tests. Mumias, Unpublished.

Kezdi, A., 1979. Soil physics, selected topics. Amsterdam, Elsevier Scientific Publishing Company.

Komba, C., 1990. Personal communication. Agricultural Engineering Section, Mumias Sugar Company limited.

Lambe, T.W. and R.V. Whitman, 1979. Soil mechanics. New York, John Wiley and Sons.

Little, T.M and F.J. Hills, 1978. Agricultural experimentation, design and analysis. New York, John Wiley and Sons.

Matete, J., 1987/88. Agricultural service annual report. Mumias, unpublished.

Raghavan, G.V., P. Alvo and E. McKyes, 1989. Soil compaction in agriculture; a view towards managing the problem. Quebec, Macdonald College of McGill University.

Revut, I.B. and A.A. Rodes (Ed.), 1969. Experimental methods of studying soil structure. Lenigrad. Kolos Publishers.

Salokhe, V.M., S. Manzoor and D. Gee-Clough, 1989. Pull and lift forces acting on single cage wheel lugs. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 891049).

Sands, R., E.L. Greacen and C.J. Gerard, 1979. Compaction of sandy soils in radiata pine forests; a penetrometer study. Australian Journal, Soil Research 17: 101-113.

Schuler, R.T and B. Lowery, 1986. Long term compaction effect on soil and plant growth. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 861048).

Soehne, W., 1953. Distribution of pressure in the soil and soil deformation under tractor tyres. Grundlagen der Landtechnik, Heft 4: 49-63.

Soehne, W., 1958. Fundamentals of pressure distribution and soil compaction under tractor tyres. Agricultural Engineering 39: 276-281, 290.

Steel, R.G.D. and J.H. Torrie, 1987. Principles and procedures of statistics, a biometric approach. London, McGraw-Hill Book Company.

Taylor, J.H., H.C. Burt and A.C. Bailey, 1980. Effect of total load on subsurface soil compaction. Transactions of the American Society of Agricultural Engineers 23(3): 568-570.

Taylor, H.J., E.C. Burt and R.K. Wood, 1986. Subsurface soil compaction beneath dual and single tyres. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 861046).

Taylor, H.J. and G.E. Monroe, 1889. Effect of dualing tires on soil compaction. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper number 891052)

Traux, W.E., K.L. Campell, G.L. Smith and R.E. Guster, 1985. Year book. Ackron, Ohio, Tire and Rim Association Inc.

Vanden Berg, G.E., W.F. Buchele and L.E. Malvern, 1958. Application of continuum mechanics to soil compaction. Transaction of the Agricultural Engineers of America, 1: 24-27.

Wambia, J.M. 1979. An economic evaluation of the Kenya sugar industry, the case study of Mumias Sugar Scheme, University of Nairobi, Thesis.

Wells, C.B., 1959. Core samplers for soil profiles. Journal of Agricultural Engineering Research, 4: 260-266.

Wood, R.K., E.C. Burt and C.E. Johnson, 1989. Dynamic load effects on thrust components along the soil-tyre contact zone. St. Joseph, Michigan, American Society of Agricultural Engineers (Paper No. 891053).

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