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Peter Shipton

Optimisation of cricket pitch rolling

Supervisor: Dr. Iain James

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Abstract

In the game of cricket, where a ball is bounced on a natural clay soil pitch between the 'bowler' and 'batsman', the ball-surface interaction is critical and is one of the most important factors responsible for the quality of play. Rolling of the playing surface with a smooth-wheel roller is common practice and this is intended to encourage pace, but with a predictable ball bounce that will provide a fair and safe playing surface.

Current rolling management is largely based on anecdotal evidence and little work has previously being carried out in the UK to quantify the effects of rolling on cricket soils or to determine optimum rolling practice. Initiatives by the England and Wales Cricket Board (the project sponsors) to advance the commercial viability of the game of cricket and to increase player participation provide commercial justification for this project. This thesis aims to improve the fundamental understanding of the scientific principles of pitch preparation and to develop practical guidelines on roller use to help cricket groundsmen produce playing surfaces with the desired playability characteristics.

A diverse methodology was used to meet the project objectives. A survey of current practice was conducted to inform experimental design and inform the targeting of rolling guidelines. Dynamic and static triaxial experiments were combined with standard laboratory tests to establish soil mechanical parameters for cricket soils. Field experimental plots and a project designed rolling simulator were used to investigate the interaction between soil mechanical and roller physical properties and to establish rolling management protocols. A grass rooting experiment was also conducted to determine the effect of soil density on root growth and distribution within the compacted soil profile.

The survey of current practice established a wide range in rolling practice, particularly in the time allocated to rolling in the spring and for summer pre-match rolling. The experimental results developed the relationship between moisture and soil mechanical properties of cricket soils indicating an increase in plastic and elastic strain with an increase in moisture in un-saturated soils. An increase in soil moisture from 16% to 25% gravimetric moisture content was also shown to increase horizontal movement under a towed roller; however the inclusion of grass roots into the soil profile considerably reduced soil displacement. Soil optimum moisture conditions were identified for a range of roller specifications; 24% gravimetric moisture for a 750 kg m^{-3} roller and 22% for a 920 kg m^{-3} roller. Roller speed (0.7 km h^{-1}) and the amount of roller passes required (four passes of a two drum roller in the spring and a total of 10 passes for summer match preparation) were established for cricket pitch preparation. Results also indicated a significant potential to reduce annual rolling times when undertaken in optimum soil moisture conditions. This could result in a substantial reduction in cost to the cricket industry and a reduction in CO_2 emissions.

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Notation

A_v	air voids (%)
c'	effective cohesion (kN m^{-2}, kPa)
c_s	cohesion at saturation (kN m^{-2}, kPa)
G	gravities (G)
K_0	coefficient of earth pressure at rest (1- sin ø (internal angle of friction))
k_d	Soil stiffness under a dynamic load (kN m^{-2}, kPa, MN m^{-2})
ϕ	angle of internal friction (degrees °)
P_{at}	atmospheric pressure (kPa)
PR	penetration resistance (MPa)
q	deviatoric stress (kN m^{-2}, kPa)
$u_a - u_w$	the matric suction (kN m^{-2}, kPa)
ε	strain
ε_{max}	maximum axial strain (mm)
ε_v	volumetric strain (%)
θ_m	gravimetric moisture content (%)
θ_{opt}	optimum moisture content (%)
θ_r	volumetric water content at residual conditions (%)
θ_s	saturated volumetric water content (%)
θ_v	volumetric water content (%)
μ	pore pressure (kPa)
ρ_s	particle density (g cm^{-3})
ρ_b	bulk density (g cm^{-3})
ρ_d	dry bulk density (g cm^{-3})
ρ_{dsat}	saturated bulk density (g cm^{-3})
ρ_s	particle density (g cm^{-3})
σ	normal stress (kN m^{-2}, kPa)
σ'	effective stress (kN m^{-2}, kPa)
σ'_h	earth pressure at rest (kN m^{-2}, kPa)
σ'_{ht}	triaxial Earth pressure at rest (kN m^{-2}, kPa)

σ'_v	vertical effective stress (kN m^{-2}, kPa)
σ_1	principal stress (kN m^{-2}, kPa)
σ_2	intermediate principal stress (kN m^{-2}, kPa)
σ_3	minor principal stress - radial stress (kN m^{-2}, kPa)
σ_{max}	maximum axial stress (kN m^{-2}, kPa)
τ	shear stress (kN m^{-2}, kPa)
τ_u	suction strength (kN m^{-2}, kPa)

Cricket terminology

Bounce	degree of ball elevation after impact, measured as ball rebound %
Compaction	reduction in pore space leading to an increase in dry bulk density resulting from a temporarily applied load
Consolidation	reduction in pore space due to a static applied stress inducing a slow dissipation of pore pressure as pores drain in a saturated soil
Dry bulk density	mass of oven dried soil in a given volume, g cm^{-3}
Ground	cricket match venue
Pace	a measure of retained ball speed after impact
Pitch	section of the cricket square prepared for a game of cricket (alt. strip, wicket)
Prepared pitch	pitch ready for match play
Roller pass	travelling of one roller drum over a specific area
Square	area of the cricket ground where pitches are created (alt. table)
Strip	alternative for cricket pitch
Test match	International match played between different nations over a five day period
Topdressing	additional soil applied to the surface to maintain surface evenness
Wicket	prepared pitch ready for play

For data interpretation throughout, statistical significance is denoted as follows: ** $p < 0.01$; * $p < 0.05$; LSD (95%) = least significant difference at the $p = 0.05$ level.

Chapter 1. Introduction

One of the most important factors responsible for the quality of play in the game of cricket is the surface on which the match is played. Cricket has evolved over many centuries and as player technique and skill has changed the playing surface has increasingly influenced both play and results. The interaction of the ball with the surface is critical and influences ball bounce, trajectory and pace (Baker *et al*, 1998c; James *et al*, 2004). The role of the groundsman in providing a suitable surface is vital to ensure enjoyment from participation, entertainment for spectators and success to the most skilful.

The current recommendations (Adams *et al*, 2004) for soil type and soil physical conditions for match play on First Class pitches in the UK are for a soil with a clay content of 27% - 33%, dry bulk density of 1.65 – 1.75 g cm^{-3} and a gravimetric moisture content of 18 – 20%,

Pitch preparation should encourage pace by reducing the degree to which ball speed reduces after surface contact, but with a predictable ball bounce that will provide a fair and safe playing surface. This is currently achieved by even compaction of a clay loam soil pitch with a smooth wheeled roller in the spring before the playing season and again before and during a match.

The procedure for rolling has evolved over time and is largely based upon tradition and individual trial and error. The ‘art’ of the groundsman in preparing a specific pitch in its unique circumstances is not to be underestimated, however lack of a clear directive on effective roller use has contributed to a high degree of variation in prepared pitches at all levels and from game to game at the same venue (Baker *et al*, 1998a).

The commercial sponsors of this project are the England and Wales Cricket Board (ECB), the governing body of cricket in England and Wales and are providing funding as part of their commitment to improving the vibrancy (viability and popularity) of the domestic game. The remit from the sponsors for this project is twofold:

1. To improve the understanding of the scientific principles of cricket pitch rolling.
2. Produce guidelines for the effective rolling management of pitches at all levels of the game.

1.1 Thesis structure

Chapter 1:

Chapter 1 discusses the background to the project, the sponsors situation and purpose and where rolling optimisation sits within their overall business strategy. The chapter then evaluates the current knowledge surrounding rolling practice and best practice recommendations. The remainder of the chapter discusses trends in research and areas of theoretical weakness associated with cricket pitch rolling and a review of other work from outside the cricket industry that the project has been able to draw on to aid in the development of the project objectives.

Chapter 2:

Having identified the weaknesses in the current understanding Chapter 2 establishes the nature of the problem, what is going to be researched and why. This leads to the generation of aims, objectives and hypotheses to be investigated.

Chapter 3:

Assessment of current rolling management was investigated by a survey of cricket groundsmen to determine the extent of any variation in cricket pitch rolling management regimes in the spring and for match preparation, and also to determine any differences in rolling management between different levels of cricket. The results also informed design for the field experiments.

Chapter 4:

Chapter 4 presents results of physical and mechanical characterisation of the two soils used in the experiments. Working on a hypothesis that soil mechanical properties change in relation to the soil moisture, static and dynamic laboratory strength and compaction tests are described. These experiments enabled the characterisation of the relationship between moisture, initial dry bulk density and soil compaction in terms of mechanical parameters, stiffness and elasticity, for repetitive loads to increase soil dry bulk density (ρ_d).

Chapter 5:

To transfer the understanding of soil mechanical properties, and their influence on the effectiveness of rolling under different soil physical conditions with the interaction of grass roots within the soil profile, controlled field experiments were necessary. Chapter 5 reports the results of five rolling experiments undertaken to determine the effect of roller load and speed in a range of soil physical conditions and the analysis of moisture loss from the soil profile during summer pre-match drying.

Chapter 6:

The extent to which grass roots can penetrate compacted cricket soils and their influence on pitch profile drying has not been previously established. Grass leaf and roots have important functions in pitch preparation and playability parameters, in particular their contribution to soil drying. Chapter 6 presents the results of an experiment designed to gain a greater understanding of the limitations of rooting in compacted cricket soils and the affect of grass roots and soil dry bulk density on cricket pitch profile moisture content.

Chapter 7:

Chapter 7 reports the results of a cricket rolling simulator that was designed and constructed specifically for the purposes of this research with the intention of gaining an improved understanding of the effect of rollers of different diameter, speed and load on soil movement and changes in bulk density (ρ_d) within the profile under different soil moisture conditions. The simulator enabled the testing of these roller parameters in different moisture conditions as well as measuring the pressure distribution through the soil profile.

Chapter 8:

Discussion of the experimental work presents a conceptual model of cricket pitch rolling with justification of the concept from experimental data. Discussion of practical considerations for pitch rolling and match preparation that evolved from the experimental work, lead to suggestions for cricket rolling guidelines. The implications for the sponsors of the thesis results and a financial appraisal are also included.

Chapter 9:

The final chapter of the thesis aligns the project objectives with the thesis conclusions, an appraisal of the contribution to knowledge made by the experimental work, research limitations and suggestions for future work.

1.2 The game of cricket

Cricket is a global sport and is governed internationally by the International Cricket Council (ICC). The ICC currently has 104 member countries of which 10 are classed as full members, one of which is the UK, allowing them to participate in official test cricket. In the UK the England and Wales Cricket Board (ECB) are the governing body of cricket. However the professional game consists of 39 financially autonomous County Boards which participate in 4 leagues (with the exception of the County Board of Wales) as well as being the source of the National squad that are in addition to the 12 elite players that are contracted centrally to the ECB. A total of 424 focus clubs provide support to the counties through facility use and youth development, and in excess of 5600 other clubs participate in the sport (ECB, 2008).

Overall participation is currently growing with a 27% increase (47% increase in female participation, 22% increase in black and ethnic minority groups) reported for 2006/7 (Collier, 2008). However between 1994 and 2002 a 2% decline in participation in cricket at secondary schools was associated with a trend of declining educational sports facility provision and notably a 47% decline in access to cricket practice facilities (nets) (Sport England, 2002). The recent increase in participation can therefore be attributed, at least in part, to initiatives to increase participation undertaken by the ECB.

The game is contested by two teams of eleven players, however there are a number of different forms of cricket which are largely differentiated by the duration of the match which can be determined by over's (a series of six ball deliveries) or a time limit. At the professional level the following formats are played:

- International Test cricket – up to 5 days duration
- One day international cricket – limited to one 50 over innings per team
- International Twenty20 cricket – 20 overs per team
- First class, county level cricket – duration depending on the competition but comprises 4 day or limited overs (20, 40 or 50 overs) cricket

The amateur cricket player will play for a club with games generally completed in one day, either through over limitation or the allowance of one innings per team.

Although artificial playing surfaces are sometimes used at the lower levels of the game matches are normally played on a natural turf surface in the UK. Outside the UK, particularly away from the professional game, artificial pitches are more common. Currently 74.4% (1589 out of 2136 grounds) (ICC, 2007) in countries associated or affiliated (i.e. not full members) to the ICC have artificial playing surfaces.

In the centre of a cricket venue ('ground') is a 'pitch' which is a 20.12 m x 3.66 m strip where each team has a turn at scoring runs after hitting a ball that has been bowled at them by the opposing team. A crucial ball/surface interaction occurs when the bowled ball is intentionally bounced off the playing surface before it reaches the batsman.

A natural turf pitch is one of a series of potential playing surfaces produced by the groundsman from the cricket 'square' which is constructed in the UK from a minimum of 100 mm depth of soil selected for cricket playability characteristics. Soils with variable mineral contents occur and Baker *et al* (1998a) determined a range of <20% to 40% clay from 325 first class pitches.

Pitches are prepared for a match by rolling with a smooth wheeled roller with the intention of improving pace, consistency of bounce and surface hardness. Pace has been defined as a measure of retained ball speed after impact (James *et al*, 2004) although historically it has been measured subjectively by umpires and players with pitches being categorised into slow, medium or fast paced. Consistency of bounce is a subjective attribute and has not been quantified (James *et al*, 2004). Hardness is the resistance to deformation (see Section 1.5.3.1) and has a consequence on bounce, pace and angle of trajectory after impact.

Rolling is traditionally undertaken in March/April before the playing season starts and is also carried out prior to a match. Water may be applied to aid compaction depending on soil moisture conditions and the groundsman's idea of correct practice. A wide range of roller types are found on cricket grounds (Figure 1.1).

Figure 1.1 Roller specification and configuration vary according to venue, use and finance.

1.3 England and Wales Cricket Board business strategy

Formed in 1997 to take over the responsibilities carried out for the previous 30 years by the Test and County Cricket Board (TCCB), the National Cricket Association (NCA) and the Cricket Council, the ECB needs to ensure that its strategic agenda fits well with the values and ideology of the organisation. The ECB sets these out in its 'vision' for the future in a document entitled 'Building Partnerships'(ECB, 2005). This details their goals (effective leadership and governance, a vibrant domestic game, enthusing participation and following (especially among young people) and successful England teams) and a strategy to achieve them by 2009.

Business strategy is concerned with the positioning of a business in its chosen market with the aim of satisfying the stakeholders' expectations. It has been defined as an agenda rather than a discipline (Jenkins & Ambrosini, 2002). The strategic agenda can be developed at three different levels, the environment, the firm and the individual and is based on a series of strategic decisions.

Not all organisations are driven by profit but they will still have goals to measure success. Grant (2005) states that 'strategy is about winning' and that it plays a major role in business 'success'. Sports organisations are rarely in existence as profit orientated businesses and see sporting success as their main goal coupled with increased participation either directly through playing the sport or by supporting those that do.

Not-for-profit organisations may have diverse sources of funds and are quite likely not to be direct beneficiaries of the services offered by the source. Therefore the funds come from organisations hoping to gain from an association (media coverage and advertising revenue) or merely a funding body i.e. in the form of grants. Nonetheless the principles of competitive strategy (for funds) still hold. The fact that multiple sources of funding are likely to exist, linked to the different objectives and expectations of the funding bodies, might also lead to difficulties in clear strategic planning, and a requirement to hold decision making and responsibility at the centre, where it is answerable to external influences, rather than delegate it within the organisation (Johnson *et al*, 2005).

Sports organisations have their own specific underlying values and ideology which will be of central strategic significance and play an important part in the development of strategy because the 'raison d'être' of the organisation is rooted in such values.

Much of the ECB's work to achieve the vision is the negotiation and allocation of the funding coming into the sport from various funding bodies and in particular funds (media and sponsorship) generated by the national team. Turnover of the ECB has increased from £20m in 1997 to approximately £90m in 2007 as a result of growth in the sport. Effective allocation of this money throughout the game provides the means to achieve their goals.

The governing body's influence is greatest at the 'elite' level (test cricket and the national team) and at the 'grass roots' level (enthusing participation). The 39 cricket boards (county cricket organisers) and cricket clubs have economic autonomy although they rely on financial support provided by the ECB to supplement other income streams. By specifying conditions for qualification for funds the ECB is able to exercise a degree of influence over the boards (and to a lesser extent the clubs) in terms of player and facility strategies. Some counties though are slower to embrace the ECB vision than others which inevitably slows the process of change.

1.3.1 The sporting entertainment sector and competition

Economic theory defines a sector as 'a group of firms producing products that are close substitutes for each other'(Porter, 1980). Sports organisations produce similar products in terms of sporting entertainment therefore competition within the industry will be in the form of attraction of funds through grants and commercial partners. The public popularity of the sport will determine the level of investment from commercial partners as well as other investment streams. The ECB strategy recognises this relationship (Figure 1.2) and is channelling more than 90% of its increased budget into improving the success of the national cricket teams and increasing participation in the sport at all levels. At the same time the intention is to generate more income from commercial partners and a targeted 15% increase in supporters.

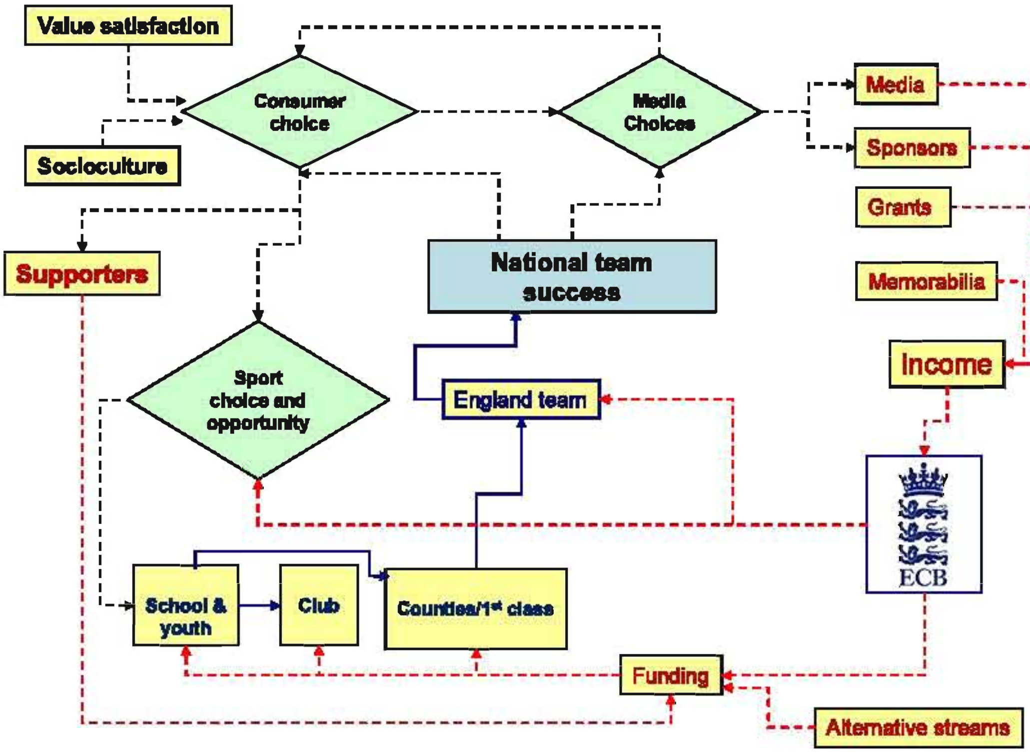


Figure 1.2 Decision and basic funding flow for ECB. National team's success affects media and consumer choice (black lines). Media choice will have an influence on income and consumer choice. Consumer choice affects participation throughout the game. Players at the top level are generated from school and youth development (blue lines) and are affected by choice and funding flows (red lines).

A strong strategic emphasis has been put on national sporting success as this is seen as 'the single most important factor in attracting players, spectators and supporters to any sport' and 'the development of successful English teams as critical to the future of cricket' (ECB, 2005). A 41.7% increase in resourcing over the five years to 2009 has been envisaged to help to improve the success of England teams.

Media income currently represents approximately 70% of the income for the ECB, however media businesses will have limited allegiance to any particular sports organisation and are driven by financial gain and/or consumer demand and make investment decisions on this basis. Marketability of the 'product' affects media value and in the case of cricket its value is reflected in worldwide demand, especially from audiences from countries of opposing national teams, India in particular. However the ability of the national team to provide an even contest and increase the drama of the match is an important bargaining factor in media negotiations.

An organisation will also need to be aware of the needs of the market segment (potential customers) that it is marketing its products to. Consumer choice for potential spectators is partly sociocultural (the mix of social and cultural background) in its trends but is also influenced by value satisfaction and media coverage. For the ECB the national team success crucially links with the main decision making processes in the network in Figure 1.2. Socioculture is inherent within society and will only change slowly over time. Channelling funding into grass-roots cricket aims to increase association with the sport from a young age in the hope that it will stay with an individual for life thus producing a growing culture of cricket players and supporters.

1.3.2 Strategic capability

The capability of a sports organisation to achieve its aims will depend on the resources and competencies available. In profit orientated businesses, the uniqueness of these attributes will be a determinant of success. In the non-profit sector these factors will play an important role in the efficiency with which it meets its targets. Increasing the level of competency through training and recruitment is often necessary as a business realigns existing strategy. Likewise, investment in resources in order that goals can be achieved may need to take place.

The ECB has a long history of working with commercial partners (currently more than 30 sponsors and partners) and therefore has proven competencies in this area of financial management. Investment is being channelled into coaching, to improve playing skill levels throughout the game, as well as funding strategies to increase participation (Figure 1.3).

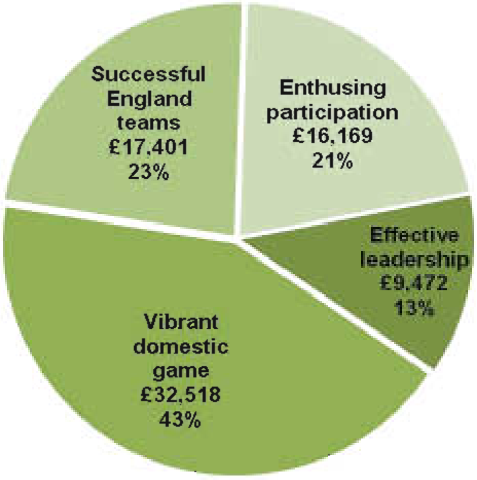


Figure 1.3 Projected expenditure (£000) for 2009 (source ECB, 2005 - Building Partnerships).

Resources are also being made available for facility improvement. The playing surface which plays such a vital role in the game of cricket has historically not been considered with such importance with regard to funding, either directly, or through groundsman training or through research into techniques and equipment. However an increase in funding into research prompted by a broader view on the drivers of success from the ECB has resulted in an increase in funding into this area.

1.3.3 ECB strategy and the games entertainment

The ECB strategy hinges in the long term on sporting success. Resources to achieve this are at an all time high level. Success on the cricket pitch is a result of individual skill together with a multitude of other small factors coming together at the same time. John Wooden (Wooden, 2005) claims that 'when you see a successful individual, a champion, a 'winner', you can be sure that you are looking at an individual who pays great attention to the perfection of minor details'.

The official ECB website (www.ecb.co.uk) recognises the importance of the pitch stating 'for as long as cricket has been played, one of the most important factors responsible for the quality of play is the surface on which the match is played'. Improvement in pitch preparation can potentially improve the height and consistency of ball bounce and pace enabling the batsman to use his skill to score runs and reduce the need to gamble on the pitches unpredictability. This accentuates the skill not only of the batsman but also the bowler whose success should also come from his skill rather than a poorly prepared playing surface. The tendency for more predictable playing surfaces is to produce higher scoring games which are considered to be greater entertainment for spectators. The spectator likes to see an even contest and a close finish to enhance excitement and value satisfaction. Predictability also enables newcomers to the game or lesser skilled players to realise greater enjoyment in safer conditions thus encouraging future participation.

Games played over a number of days at the first class or international level use the gradual deterioration in the surface to bring games to a conclusion. This is encompassed within the nature of the game and it is the skill of the team captaincy that attempts to use this to their advantage. However poor, inconsistent pitches that deteriorate quickly can reduce the length of the match reducing entertainment as well as spectator and media income.

Groundsmen require a high level of skill to achieve the desired pitch quality, particularly in the UK climate. Most of that skill is a result of historical ‘wisdom’ applied by trial and error, rather than as a result of scientific research. Scientifically derived data is necessary in order that sound practical solutions can be determined for all and not on an individual basis. It is also important that this knowledge is freely available to all groundsmen to improve the overall standard rather than to individuals for personal, sporting or financial gain.

1.3.4 ECB strategy and research

Since 1997 the ECB has encouraged a subsidised programme of education for groundsmen with currently in excess of 1100 people having received training on Institute of Groundsmanship (IOG) courses. Investment has also been made into training and employing pitch advisers to educate and aid groundsmen as well as a fund recently available to aid in machinery purchase to help with pitch preparation. However the knowledge has to be in place before it can be taught and this is only in part the case with regard to the use of a roller in pitch preparation. Although the processes to improve communication of knowledge are in place, further investment into gaining knowledge has to be made.

The potential benefits of a rolling optimisation project can be explored through a benefits dependency network (Figure1.4). The project design should provide an output that leads to the required benefits and fits into the ECB's vision.

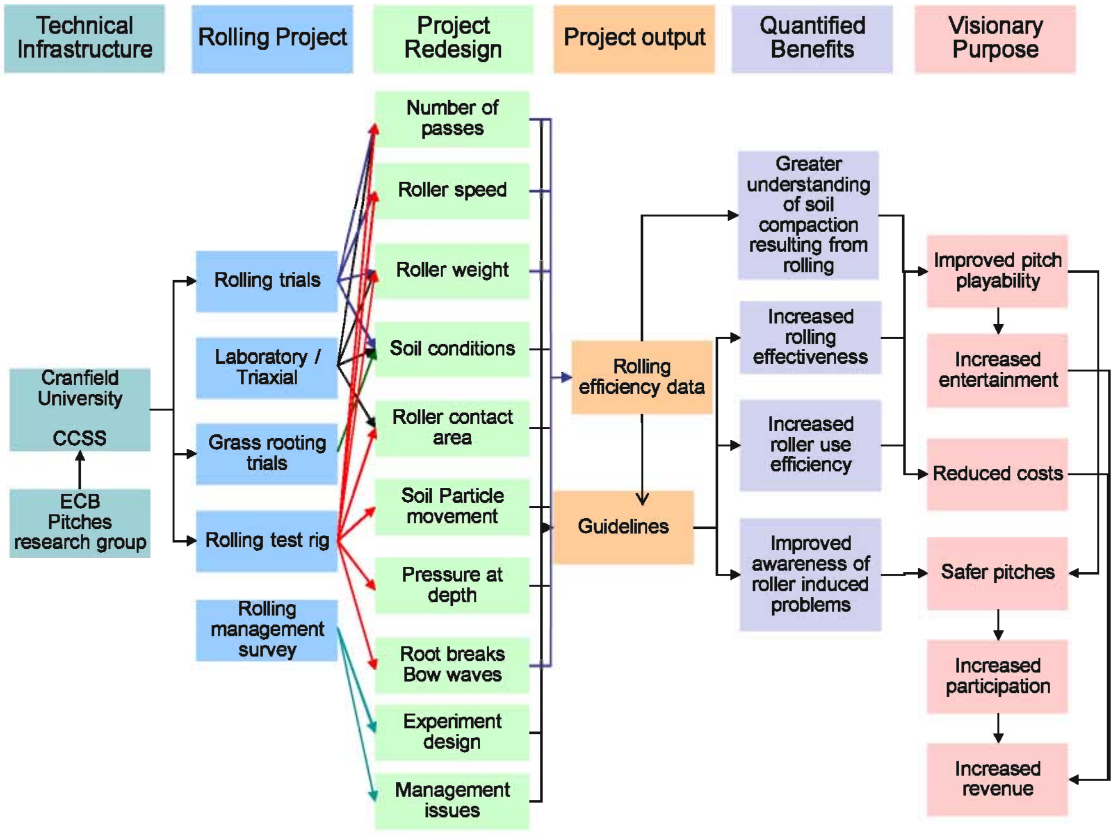


Figure 1.4 Rolling project benefits dependency network. Moving left to right, how the project design brings benefits to the ECB and aligns with their vision.

Strategy to develop cricket by enhancing skill levels and participation will maintain media interest, and therefore vital income streams, but ultimately national team success is crucial to a vibrant sport. Although success in any sport cannot be guaranteed, attention to all aspects of the game is necessary to increase the probability of fulfilling the ECB vision. Providing a suitable playing surface is a vital component in the detail that could deliver success. Research into improving the scientific understanding of pitch preparation is an essential part of the process that will provide groundsmen with new skills to produce a consistently high standard of playing surfaces.

1.4 Current thinking on playing surface requirements and pitch rolling

What constitutes an ideal pitch depends on the type of game that is to be played. The ECB (ECB, 2008) comment 'for four-day matches, the ideal pitch is one that allows every facet of the game an opportunity and every cricketer the chance to perform to their best, whether they are seam bowlers, batsmen or spinner. In one-day cricket, the pitch should be one that allows batsmen to have their day, and thus provide the entertainment that as spectators we have all grown to love'. A players view of a good pitch will invariably be biased depending on his/her role within the team and the stage of a match so should not, and could not, be a sound basis for pitch preparation guidelines. Unfortunately groundsmen are often held responsible for a team's poor performance regardless of the 'quality' of the pitch, underlining the need for a recognised standard.

The ECB's current guidelines for preparing cricket pitches (ECB, 2007) outline the objectives of pitch preparation. They refer to pitches as needing to be dry, firm and true with even bounce as criteria for all forms of first class cricket. For lower levels of the game (club and schools) the stated objective is simply that the pitch should give a consistent and safe bounce. These guidelines however provide only limited information on how to achieve these playability parameters when using a roller. Likewise the current standard training guidelines (ECB & IOG, 2003) state that the aim of rolling is to achieve 'a consolidated surface with good pace and bounce' achieved by a 'flat and firm surface'. These recommendations for spring rolling also lack detail for the correct procedure and simply suggest 'start with a light roller – then over time build up in weight ending, if possible, with a heavy roller' and 'use various weights depending on the moisture of the soil'.

Despite different match requirements, four key playing characteristics of pitches were identified by Adams *et al* (2004), apparent bounce, pace, consistency and turn. These are in turn influenced by soil texture, soil dry bulk density, moisture content, and organic matter as well as grass leaf and rooting. This report emphasised the need to reduce pitch moisture content in order to 'achieve a pitch's bounce potential' and recommend maximum gravimetric moisture contents for a prepared pitch based on data from first class matches (Table 1.1).

Table 1.1 Recommended maximum gravimetric moisture content in 0-60 mm of prepared pitches (clay 27-33%) from Adams *et al* (2004).

% organic matter	< 6%	6-10%	> 10%
Max moisture (%)	18	20	22

Furthermore a recommendation for a target dry bulk density to indicate adequacy of consolidation was proposed (Table 1.2) based on organic matter levels within the pitch soil to a depth of 80 mm. No suggestion was made as to a possible rolling strategy to achieve these targets or any different recommendations based on soil type.

Table 1.2 Target dry bulk density (no soil type specified) for the top 80 mm of prepared pitches from Adams *et al* (2004).

% organic matter	4	6	8	10	12
Dry density, g cm^{-3}	1.75	1.65	1.55	1.45	1.35

This report also considers that horizontal layering in the pitch profile is almost the sole cause of bounce inconsistency rather than cracking of the soil and cites unsuitable rolling practice as a potential cause of horizontal layering in the pitch profile. It does not however suggest what constitutes an unsuitable rolling practice and how this may result in horizontal layering.

1.4.1 Soil texture and physical conditions

Traditional practices to improve pitch playing qualities have changed as the game has developed and knowledge and players aspirations have increased. Various practices from the first half of the twentieth century e.g. the application of Nottinghamshire Marl (either as a slurry mixed with cow dung, or as topdressing) which was aimed at increasing pace and bounce but caused drainage problems, have changed as a result of a greater understanding of soil mechanical properties. The improved knowledge of the interaction of playability and soil properties over the last 60 years has provided groundsmen with an awareness of the need to manage soil, in particular the matching of topdressing soil to the existing pitch profile.

In 1968 Stewart and Adams (1968) published a paper resulting from a scheme of research sponsored by the M.C.C. (Marylebone Cricket Club, the founder of the TCCB and NCA) which discussed factors that determined the playing qualities (bounce and pace) of cricket pitches. They concluded that rolling of pitches had a limited function as playability was ‘primarily a function of the top inch’ of the soil profile and that moisture and soil binding strength were more crucial factors. The paper detailed a methodology for assessing soil binding strength, the Adams, Stewart Soil Binding test (ASSB), which determines the strength (compressive force required to shatter) of an air dried soil sample. This test has formed a basis for assessing the suitability of a soil to achieve the desired pace and bounce and can also be used to assess the compatibility of different soils for topdressing (the application of fresh soil to the existing playing surface to repair the surface). Adams *et al* (1994) showed a positive relationship between soil binding strength and vertical rebound height. They also determined a positive relationship between soil binding strength and clay content with soils containing up to 40% clay (<0.002 mm particle diameter).

Adams *et al* (2004) claim that clay contents <26% have insufficient binding strength causing potentially dangerous pitch break up and that no benefit is gained from clay contents >33%. A proviso to this suggests that low clay (minimum 24%) could be appropriate in high rainfall locations to increase drying rates. High clay soils are slower drying and more prone to shrink / swell characteristics associated with clay mineralogy. Cricket facilities with limited resources for moisture control (i.e. labour and pitch covers) may well benefit from a lower clay soil.

UK cricket soils are sourced from a number of different locations within the UK and therefore possess relatively unique physical attributes which potentially will alter their mechanical and hydrological properties. Table 1.3 illustrates some physical and mechanical properties at point of purchase from 20 standard cricket loams (ECB, 2004). 14 out of the 20 loams were classified as Clay Loams (UK Textural Triangle; Soil Survey of England and Wales; Avery and Bascomb, 1982); two were classified as Sandy Clay Loam and one classification each for Silty Clay Loam, Silty Clay, Sandy Silt Loam and Clay.

Table 1.3 Mean cricket loam particle size distribution, organic matter and ASSB strength characteristics (extracted from data supplied by ECB (2004)).

Attribute	mean %	max %	min %	range %
Sand	35.3	53.0	16.0	37.0
Silt	37.5	59.0	20.0	39.0
Clay	27.3	37.0	14.0	23.0
Organic matter	4.3	6.9	2.5	4.4
Strength	58.6	77.6	41.1	36.5
Shrinkage	15.0	23.4	3.6	19.8

No data are available as to the extent of use of these soils and it is also likely that these characteristics will vary over time from a given supply due to changes in the supplier's source of soil.

The colloidal fraction of the soil (organic matter and clay) will influence the water retention capacity of soil during pitch wetting and drying both in terms of the pore size associated with particle size and also the potential for adsorption of water molecules. Organic matter carbon atom chains have high capacities to adsorb water but exhibit no plasticity (Brady, 2002) but can be influenced by climate. Higher levels of organic colloid within a pitch profile will lead to complications in terms of drying and potentially bulk density.

It is apparent from the shrinkage data in Table 1.3 that all cricket soils have at least some element of expanding 2:1 silicate clay such as smectite or vermiculite in their mineralogy. The exact mineralogy will influence the water adsorption and hence the expansive potential of the soil which will influence soil cracking as well as soil drying rates; however it was beyond the scope of this project to investigate this aspect further due to the large variation in soils available and the time frame of the project.

Matching soil for topdressing to ensure compatibility with existing soil to avoid a layered profile is a relatively recent advancement in pitch management. Mixing soils with different mineralogy can result in differences in shrink / swell and cohesive properties leading to separation within the soil profile. However with more than 20 cricket loam 'products' commercially available, each with potentially variable soil mineralogical parameters, difficulties may arise in maintaining a pitch profile with a consistent soil type.

1.4.2 Performance quality standards

Performance Quality Standards (PQS) have been established for cricket pitches (Appendix1) and the Institute of Groundsmanship (IOG, 2004) state that they are aimed at providing a 'range of clearly defined and measurable criteria that are associated with a specified level of quality'. The Institute of Groundsmanship (IOG) splits these standards into three categories, structural, presentational and playing quality giving a minimum standard at three levels of play for a range of characteristics that can be managed. The opportunity to manipulate these standards through rolling of the surface is particularly applicable to hardness and ball rebound but also soil compaction could have an impact on grass cover, root depth and surface evenness.

1.4.3 Roller use – current thinking

Rolling of pitches has occurred for more than 200 years, initially with relatively light (approximately 250 kg) stone and then wood rollers in the early 1800's (Evans, 1991). Later horse-drawn rollers were believed to be 500 kg or more and the gradual mechanisation through the early twentieth century saw a gradual increase in the dimensions of rollers particularly the mass. With no standard roller specification advocated by any authoritative body a diverse range of dimensions and roller configurations are in use at the present day although no study has been made to ascertain the level of this diversity.

The generally stated reason for rolling is to increase the hardness and uniformity and improve the evenness of the surface. Attempts to define correct procedures have been based mainly on individual anecdotal evidence leading to a mixture of different methods and equipment. Current official guidance for rolling is restricted to the ECB/IOG training documents (ECB & IOG, 2003) which describe basic outline procedures but are limited in essential detail in particular:

1. When to roll in terms of appropriate soil conditions; soil moisture and existing dry bulk density
2. What roller design (weight, width and diameter) to use in specific soil physical conditions
3. How to roll, in terms of operational conditions; speed, frequency and roller passes

1.4.3.1 Pre-season rolling

Rolling of the playing surface is in general considered appropriate in the spring before the playing season starts when all of the pitches are rolled as part of the same management programme. Evans (1991) concedes that only generalised suggestions can be made for pitch preparation because 'all grounds are different and each responds to a particular treatment in an idiosyncratic way'. He also blames the lack of scientific research into the way soil physics and moisture influence the playing surface for the short fall in more specific advice. However he offered a recommendation for consolidation of the top 100 mm of the pitch profile for the novice groundsman suggesting rolling in the spring, 'when conditions permit', with a light roller (254 kg) for 14 passes, followed by 10 passes with a medium roller (356-508 kg) and then finally 14 passes with a heavy roller (>1000 kg) no justification was provided for these suggestions however it was noted that the groundsman should 'in future years modify the procedure based on the results obtained'. The IOG training document (ECB & IOG, 2003) suggests roller weight which are identical to Evans' (1991) but do not clarify this with roller width, diameter and number of roller drums. Furthermore no indication is made as to what weight with regard to soil moisture and existing bulk density should be adopted and how much rolling with any weight / moisture combination either in terms of time, speed or roller passes, simply stating 'rolling can only be carried out when there is sufficient moisture in the soil'. Stewart and Adams (1968) however suggest that excessive rolling may in fact be detrimental 'imposing a laminar structure where this might otherwise not exist'.

The vagueness of these guidelines (ECB, 2007; ECB and IOG, 2003; Evans, 1991) leaves them open to individual interpretation and is likely to result in a wide diversity in rolling practice. The crucial relationship between moisture, rolling and compaction is also not explained which would provide a justification for adopting a prescribed method.

Baker *et al* (2001a) carried out trials on different cricket pitch profiles to examine the effects on playing performance. In preparation the rolling regime adopted involved four roller types (Table 1.4).

Table 1.4 Time spent on pre-season rolling an area of 238 m^{-2} (Baker *et al,* 2001a).

Type of roller	16th March - 1st April 1998	15th– 31st March 1999
Heavy cylinder mower	1.5 hours	0.0 hours
Light motor roller (c. 0.25 t)	3.75	5.00
Un-ballasted twin drum roller (1.42 t)	32.25	25.00
Ballasted, twin drum roller (1.93 t)	14.75	21.25

No justification for this process was given and no speed or roller width was indicated. Making a number of assumptions Table 1.5 indicates possible roller drum passes performed.

Table 1.5 Roller passes based on Baker *et al* (2001a) assuming roller speed of 1 km^{-1} (2 km h^{-1} for the cylinder mower) and roller width of 0.5 m for the mower, 0.8 m for the light roller and 1.2 m for the twin drum roller.

Type of roller	16th March – 1st April 1998	15th– 31st March 1999
Heavy cylinder mower	6	0
Light motor roller (c. 0.25 t)	13	17
Un-ballasted twin drum roller (1.42 t)	325	252
Ballasted, twin drum roller (1.93 t)	149	214
Total passes of a roller drum	493	483

1.4.3.2 Pre-match rolling

Rolling of each pitch prior to its use is also considered part of the routine preparation. The TCCB and NCA (1989) produced guidelines on pitch preparation in 1989 and form the basis for much of what has become current practice. They suggest 'the rolling of the pitch should commence with the light roller when all surface water has disappeared. As the pitch dries the weight of the roller should be increased. The groundsman should use the heavy roller at every suitable opportunity prior to a match whilst any moisture content remains, but the heavy roller should not continue to be used when all moisture has gone from the pitch' (quoted from Adams and Gibbs, 1994).

Baker *et al* (2001a), in trials discussed in the previous section, rolled for 6 or 7 days prior to a match with 2 roller weights (Table 1.6) claiming that this procedure was based 'as closely as possible on procedures used on first class pitches'.

Table 1.6 Pre monitoring pitch rolling (Baker *et al,* 2001a).

Hours rolling	**11th- 14th May 1998**	**6th– 9th July 1998**	**21st– 24th June 1999**
Number of days when rolling was carried out	6	7	6
Hours rolling with a 1.42 tonne roller	8	4.5	5.5
Hours rolling with a 1.93 tonne roller	12	15.5	17.25
Total rolling time over 238 m^2	20	20	22.75

Using the same assumptions described in the previous section, due to a similar lack of detail, the number of passes of a roller drum over an area of the pitch have been calculated to be in excess of 100 (Table 1.7) and this would be considerably more if rolling speed was reduced to 0.3 km h^{-1}.

Table 1.7 Pre match roller drum passes based on Baker *et al,* 2001 assuming roller speed of 1 km^{-1} and roller width 1.2 m.

Roller passes	**11th – 14th May 1998**	**6th – 9th July 1998**	**21st – 24th June 1999**
Passes rolling with a 1.42 tonne roller	40	23	28
Passes rolling with a 1.93 tonne roller	61	78	87
Total roller passes over 238 m^2	101	101	115

The IOG training course manual (ECB & IOG, 2003) suggests that 'if the pre season rolling is carried out correctly there should be little requirement for heavy rolling during the playing season'. However this is contradicted in its proposal for a pre-match preparation routine where the daily use of a 'heavy' roller is recommended for at least 5 days prior to pitch use as well as on the day of use. This routine suggests rolling for 30 minutes a day (3 hours in total) 'as slowly as possible'. This would equate to approximately 15-20 passes (no mention of number of drums) for a rolling speed of 0.3 km h^{-1}. No further recommendations are made with regard to soil moisture during this series of rolling sessions other than a suggestion that if damage to grass or the surface occurs, to wait until the 'pitch has dried out further'. Evans (1991) is more cautious recognising the crucial role that moisture content could play in effective consolidation and the potential damage from rolling a pitch that is too dry although no significant rolling protocols were suggested.

The ECB guidelines (ECB, 2007) for pre-match rolling suggest starting with a light roller (254 kg) and as the pitch dries the weight of the roller should increase stating 'the groundsman should use the heavy (1ton or more) roller at every suitable opportunity prior to a match whilst any moisture content remains'. No guidance is given as to the amount of roller passes or the appropriate moisture content.

Although each cricket venue has different characteristics and one groundsman's methods may not necessarily be appropriate for another, the fundamentals of roller use are likely to be the same for all situations. The basic questions of when to roll, what roller, how much to roll and at what speed are fundamental to successful pitch preparation. However the lack of scientific research directly related to the rolling of UK cricket soils has lead to a limited understanding of the relationship between compaction, rollers, roller specifications and roller use. This has resulted in groundsmen seeking their own solutions through trial and error which are not actively shared beyond immediate colleagues. Lack of communication between groundsmen either because they work in isolation or because they are often in competition with each other prevents the flow of knowledge, good or bad.

1.5 A review of literature relevant to the rolling optimisation project

Although knowledge of rolling of a cricket pitch in the UK is almost entirely anecdotal this project can draw on relevant research from other areas. The relationship of cricket playability to soil bulk density and moisture, and the role of turfgrass roots in soil strength, have been studied and provide a basis for examining the current target levels of dry bulk density for pitch preparation.

Research has been undertaken into rolling of soil to increase bearing capacity in civil engineering and with a view to reduce compaction in agriculture to increase yield potential and therefore this provides background knowledge on rolling, despite involving different roller and soil parameters.

The underlying soil mechanics of compaction forms the basis of a scientific understanding of compaction under a dynamic load, and in particular, the relationship between material deformation and states of stress.

1.5.1 Cricket playability

Improved playing quality is the ultimate aim of the rolling process. Adams and Gibbs (1994) suggest that pitch quality is 'determined by the bounce characteristics of the ball which depends on the nature of the soil'. These parameters have been described and measured in a variety of ways with methods evolving over the last 30 years.

1.5.1.1 Ball rebound and pace

Soil mechanical behaviour, which is affected by soil physical conditions, affects the elastic-plastic characteristics of soil. Guisasola (2008) concluded that the plastic component of the soil increases the contact time between the ball and the surface reducing peak impact loads and moderating soil behaviour. It was also concluded that the elastic component of soil is essential for energy return to the ball. Stewart and Adams (1968) proposed that an objective test was required to assess 'pace' rather than relying on subjective player and umpire opinions on pitch performance. They devised a ball bounce test to assess pace which required dropping a cricket ball from 16 feet (4.88 m) onto the playing surface and then measuring the bounce height. Correlations between strength (as measured by the ASSB test) and bounce were determined. No correlation was determined for bounce and clay content or bounce and moisture content. This lead to predictions of minimum clay contents, based on ASSB results, for pace i.e. 22% clay for better than slow pace and >30% for a fast pitch. Qualifying this further (Stewart & Adams, 1969) concluded that a soil with greater than 33% clay was required for 'fast' pitches. They also concluded that the ASSB test could be used to predict pace. The ball bounce test is still used (albeit from a height of 3 m and will be referred to as ball rebound) and is part of the PQS discussed in Section 1.3.2, however it is now more likely to be considered a predictor of potential bounce.

Attempting to match pitch performance to soil physical characteristics Baker *et al* (1998a) correlated soil texture, organic matter, dry bulk density and moisture derived from soil cores removed from 325 first class pitches during 1996 and 1997, to umpires assessments and match scores using cluster analysis. Ball rebound positively correlated with sand percentage and negatively with volumetric moisture content. Pace (measured by an umpire's subjective assessment) showed a significant positive correlation with bulk density and sand content and a negative correlation with moisture, silt content and organic matter. No correlations were determined between pace and clay content. It was noted that speed of drying due to differences in sand content may have produced the correlation between sand and pace rather than the sand content itself and that 'under good drying conditions increased clay content is liable to be associated with harder wickets'.

Adams *et al* (2001) attempted to correlate umpires' assessments with playability predictors, hardness (measured by a Clegg hammer (an accelerometer calibrated to a weight dropped on to the surface with measurements in gravities (G) (Clegg, 1976; Lush, 1985) and ball rebound (3 m drop height). Results indicated that a lower moisture and a higher dry bulk density were likely to lead to a faster pace (as assessed by umpires) however the most important factor responsible for reduced pace and bounce was discontinuity at depth caused by lack of soil cohesion (layering). Other conclusions of this work were that vertical rebound provided a more reliable indication of perceived bounce and that hardness was an unreliable predictor of bounce as perceived by umpires.

To assess the relationship between hardness and ball rebound Baker *et al* (2001b) determined a significant correlation between Clegg hammer measurements and ball rebound and suggested the heavier hammer (2.25 kg) gave a better correlation than the light hammer (0.5 kg) (Table 1.8).

Table 1.8 Relationship between ball rebound and hardness (2.25 kg hammer). (Baker *et al*, 2001b).

Ball rebound, %	Hardness, gravities
10	200
16	300
20	400

Baker *et al* (1998c) measured hardness, ball rebound and pace and related them to playing quality using specially constructed soil profiles (Baker *et al*, 1998b). Pace was measured objectively using a bowling machine with an incoming velocity of 32 m s^{-1}, approach angle of 14° and a backspin of 56 rad s^{-1}. A series of significant correlations were determined but essentially moisture and organic matter had a negative correlation with hardness, ball rebound and pace whereas bulk density had a positive correlation with all three parameters. Clay plus silt content had a negative correlation with the playability parameters but this was considered to be more likely a result of slower drying rates associated with higher clay soils, a finding in agreement with similar work (Baker *et al*, 1998a).

James *et al* (2004) used high speed video capture to measure the dynamic behaviour of cricket balls on impact. Pace was measured as the predicted percentage of impact speed retained after impact and bounce was measured as a ratio of impact and rebound angle. Results indicated a decline in ball speed retained after impact (reduced pace) with increasing soil clay content and an increase in speed retention (faster pace) occurred with declining moisture. A positive correlation between moisture and clay content was also reported. It was also shown that players' and observers' subjective analysis were in agreement with the results of bounce height, consistency and retained speed.

Clegg hammer and ball rebound are currently considered adequate predictors of bounce but Adams *et al* (2004) conclude that it is not possible to assess the pace of a pitch visually. They also suggest target rebound heights as 18% (from a 3 m drop), a Clegg hammer target value of 360 g (2.25 kg hammer dropped from 450 mm) and define consistency of bounce as <20% coefficient of variation in rebound height from a ball dropped vertically onto the surface from 3 m, or <15% coefficient of variation in hardness.

1.5.1.2 Pitch organic matter and bulk density

Baker *et al* (1998b) determined that bulk density was influenced by organic matter content and that soil moisture was influenced by organic matter as well as clay content. Stock and Downes (2008) determined that an increase in organic matter from 1% to 4% resulted in a linear decline in bulk density in glacial till. They also determined an increase in water retention potential with organic matter.

Utilising trial profiles previously used for other work (Baker *et al*, 1998b; 1998c), Baker *et al* (2001a) determined that soils with higher organic matter content had lower bulk density and higher moisture contents after a simulated match preparation regime (see Section 1.3.3.2). Other results indicated that ball rebound and hardness were influenced by moisture and organic matter but not by clay content.

Data gathered from 1,018 first class matches through a pitch core sampling programme sponsored by the ECB enabled Baker *et al* (2003a) to categorise values of organic matter, moisture and bulk density into five categories, unusually low (bottom 10% of values), relatively low (bottom 25% of values less lowest 10%), normal (middle 50% of values), relatively high (Top 25% of values less top 10%) and unusually high (top 10% of values) (Figure 1.5).

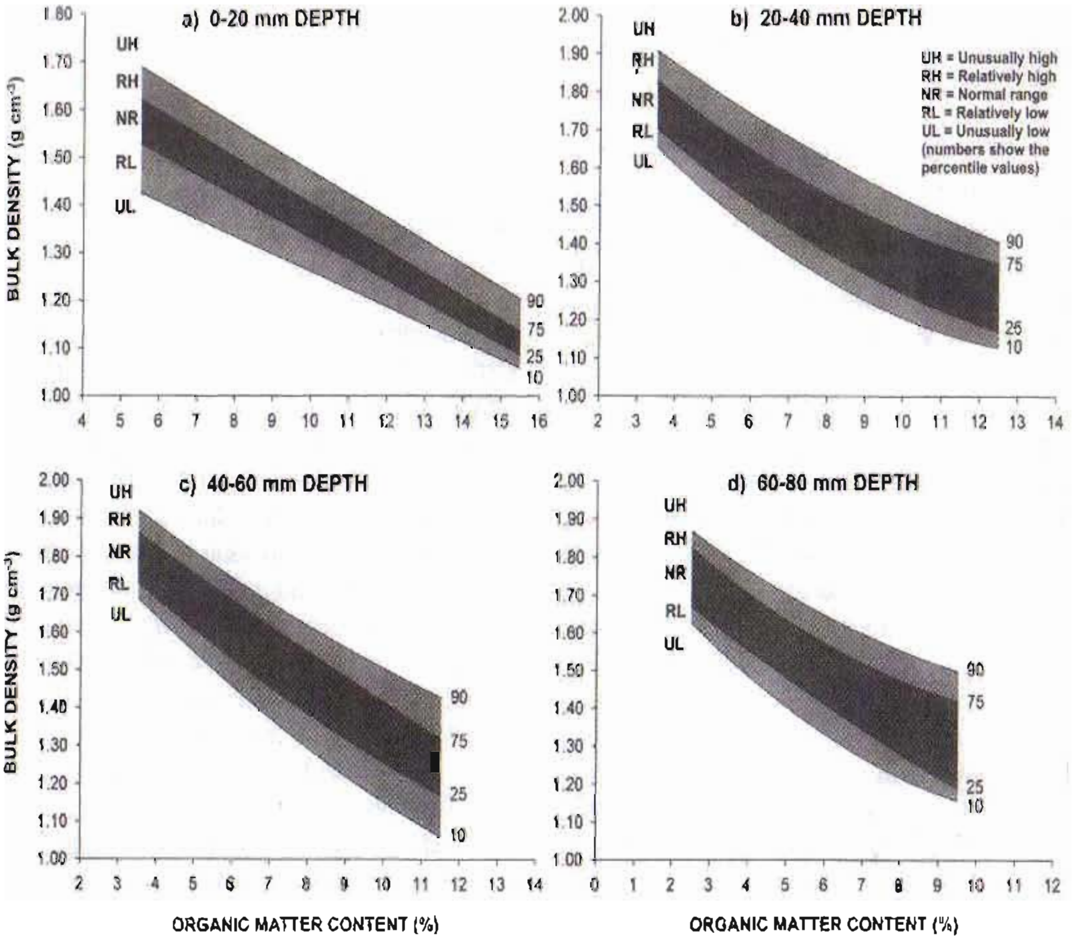


Figure 1.5 Classification of bulk density in relation to organic matter content. Unusually low (UL), relatively low (RL), normal range (NR), relatively high (RH), unusually high (UH). (Baker *et al*, 2003a). These relationships indicate declining bulk density with an increase in organic matter at four depths to 80 mm.

In a subsequent paper (Baker *et al*, 2003b) assessment of the use of this system was made. Measured by umpire's visual assessment an increase in dry bulk density below 20 mm associated with increasing bounce and pace as did a reduction in gravimetric moisture content. However the top 20 mm of the pitch profile was associated with a decline in bounce with increasing dry bulk density as well as with low moisture and high organic matter. The authors' tentative explanation for this anomaly was that greater deformation of the surface could result in an increase in ball trajectory after impact. A further cause was suggested as the increase in the elasticity of the surface could result in higher perceptions of bounce by the umpires. In conclusion they stated 'the aim should be to achieve bulk density values greater than or within the normal range at all depths between 20-80 mm' (Figure 1.5), and similarly for moisture 'values should be lower than or within the normal range'. The recommendations of Adams *et al* (2004) (Tables 1.1 and 1.2) appear to be a simplified précis of these.

1.5.1.3 Pitch cracking

Adams *et al* (2004) state 'whilst pitches with visible cracks have inconsistent bounce, the cracks themselves are not the cause of the problem' and 'inconsistency of bounce is due to the occurrence of horizontal breaks'. One possible cause of horizontal breaks was stated as unsuitable rolling practices.

Baker *et al* (1998b) investigated crack length in a range of soil types. Inconclusive results lead to the conclusion that 'cracking was likely to be the result of a complex interaction between clay content, clay mineralogy and organic matter'. This work provided no indication of cracking with regard to moisture or dry bulk density. Likewise Baker *et al* (2001a) found limited correlation between patterns of cracking and laboratory determined binding strength and shrinkage.

1.5.2 Soil mechanical properties

The subject of soil mechanics is wide ranging and applicable to this project in a number of areas. Techniques of classical soil mechanics are mainly concerned with the shear strength of idealised rigid-plastic soils and its application to the solution of stability problems; Hettiaratchi *et al* (1980) claim 'the methods of classical soil mechanics are strictly limited to the analysis of soil loads and do not deal with the shear behaviour of soil prior to or after failure'.

Sources of reference can be derived from the agriculture sector and in particular from the field of terramechanics, although much of this work concentrates on wheel/surface interactions which to a large extent are beyond the scope of this project.

1.5.2.1 Soil compaction

Abebe *et al* (1989) defined soil compaction as 'a volumetric strain or the packing of particles to a denser state as a result of an applied load'. The resultant increase in bulk density comes from a reduction in the volume of voids within the soil as the solid material is assumed to be uncompressible as is water in the soil. Voids are either air and/or water filled with the increase in bulk density being a reduction in air voids and therefore by definition soils at saturation cannot be compacted.

This change in state can be quantified in terms of change in pore volume:

$$v = 1 + e \qquad \textbf{[1.1]}$$

or change in specific volume:

$$V = \frac{\rho_s}{\rho_d} \qquad \textbf{[1.2]}$$

where v = specific volume, e = void ratio, ρ_s = soil particle density and ρ_d = dry bulk density (Hettiaratchi & O'Callaghan, 1980).

Standard laboratory tests for assessing compactability as a function of soil moisture content use a specific compactive effort to derive an optimum moisture content for compaction. The commonly used standard Proctor test was developed by Proctor (1933) in connection with the construction of earthfill dams in California on behalf of the American Association of State Highway Officials (AASHO test designation T.99-38; B.S. 1377: 1948, test no.9) (Figure 1.6). This test uses a 2.5 kg rammer dropped from a height of 300 mm 27 times for each of three layers packed into a mould to compact soil at different moisture contents. The 'modified AASHO' test was developed to give a heavier standard of compaction for airfield construction and uses a

4.5 kg rammer dropped from a height of 450 mm; this is an increase in potential energy from 7.35 J to 19.9 J. Parsons (1992) determined good correlation between the standard test (Proctor) and smooth-wheeled roller compaction.

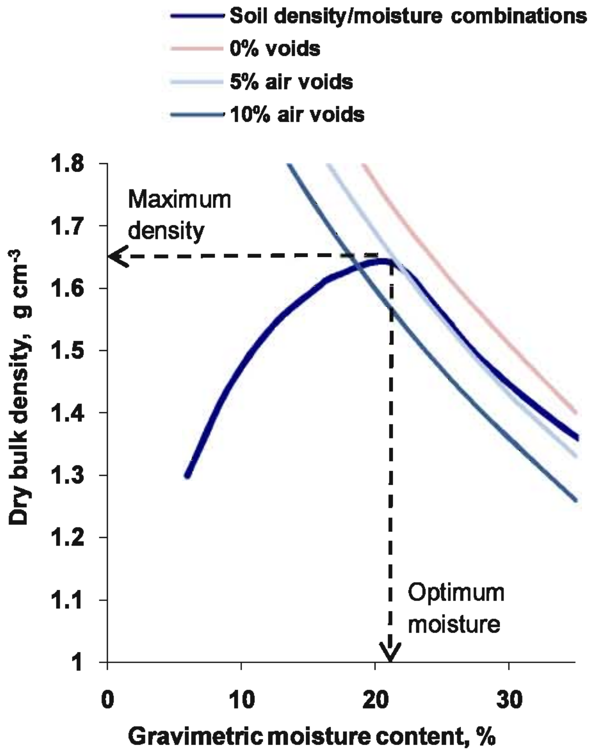


Figure 1.6 Idealised Proctor curve showing optimum moisture content and maximum dry bulk density for a given soil textural type relative to soil air voids.

Soil moisture content below the optimum for a given soil textural type results in a soil with greater shear strength requiring a greater compactive effort than is provided therefore the achievable dry bulk density is lower. Increasing moisture content increases the film of adsorbed water around soil particles reducing friction and pore water suction enabling closer packing of soil particles. Moisture content above the optimum fills available voids with water and increases pore water pressure under load due to the reduced compressibility of water compared with the air that it replaces. Expulsion of all the air from a soil results in a state of saturation i.e. zero air voids, however in practice this is unattainable (from a compactive load) and laboratory tests derive optimum moisture contents which are generally close to 5% air voids (DSIR, 1951). With moisture above the optimum the resultant air voids fall between 0% and 5% during the Proctor test.

Aggregation of soil particles over time creates macropores within the soil structure. Macropores (0.08 – 5 mm diameter) allow drainage by gravity however, due to a lower skeletal resistance, macropores are the most likely to be reduced through dynamic compaction (Adams and Gibbs, 1994). Micropores (below 0.03 mm) are increasingly unlikely to be reduced as a result of dynamic compaction but their existence will be reduced through long term overburden stress and chemical bonding. Plant root hairs can penetrate pores to 0.005 mm (Brady, 2002) and can therefore remove moisture for growth and soil profile drying. Cricket pitch rolling compaction will inevitably reduce drainage and potentially have a lower level of air voids at field capacity (moisture content after gravitational drainage). An air-filled porosity below 10% could adversely affect grass health and growth (Batey & McKenzie, 2006). Drying of the clay loam soil increases interparticle suction and reduces pore size thus increasing dry bulk density. An increase in dry bulk density can also occur due to consolidation through soil shrinkage and also occurs as a result of long term static stress and this is discussed further in Section 1.5.2.3.

1.5.2.2 Stress / strain relationship and elasto-plastic behaviour

Responses to an external load applied to soil will depend on the amount of force applied and soil physical parameters i.e. mineral composition, initial bulk density and moisture and confining pressure. Stress induced strain of a material is termed stiffness (the resistance of an elastic body to deflection or deformation by an applied force) and the slope of a curve representing the stress-strain relationship is termed the stiffness modulus (Equation 1.3).

$$\varepsilon = \frac{\delta\sigma}{\delta\varepsilon} \qquad \textbf{[1.3]}$$

where σ = stress (kPa) and ε = strain (mm).

Figure 1.7 shows an idealised stress strain relationship for soil. Between points A and B the soil is linearly elastic recovering all of the strain on the release of the stress (Hookean behaviour). At the yield (stress) point B plastic strain occurs which is not completely recoverable on stress release and therefore results in some permanent deformation of the soil. A point is eventually reached where a steady state of unrestricted flow occurs (C).

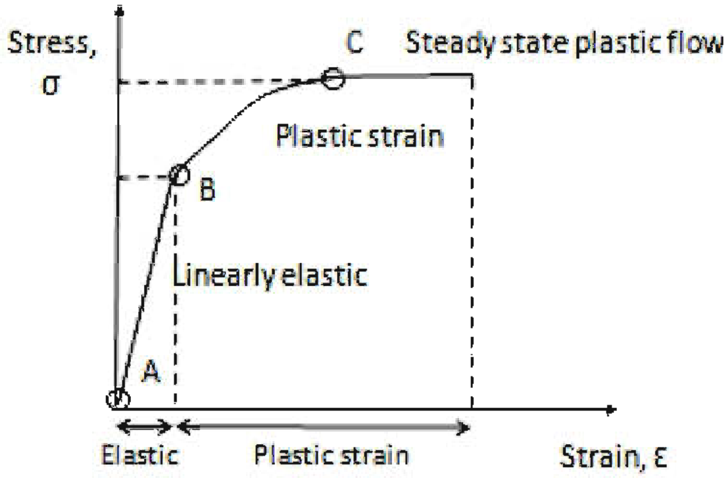


Figure 1.7 Idealised stress / strain relationship in soil. A to B elastic, B to C plastic and after C steady plastic flow.

At point C in Figure 1.7 a soil will have reached the maximum stress that the soil structure can withstand. This point can be a measure of strength in terms of shear strength and as such can be defined as ‘a maximum value of shear stress that may be induced within its mass before the soil yields’ (Whitlow, 2001). Elastic strain is relatively small in soil compared to other materials (Spoor, *et al*, 2003) and the shape of the stress/strain relationship will be influenced by initial bulk density and soil mineralogy.

Rolling of soil applies stress for a short period of time before the stress is released allowing recovery of elastic strain with residual plastic strain increasing bulk density and soil stiffness. Karmaker and Kushwaha (2005) showed that elastic and plastic behaviour depends on the load magnitude and the rate of loading.

The National Physics Laboratory defines hardness as the ‘various properties of matter that give it resistance to plastic deformation when force is applied’ (NPL, 2008). In terms of cricket pitch hardness deformation by a cricket ball will depend on the force of ball impact and the resistance to deformation of the soil which in turn is dependent on soil plasticity. Plasticity of the soil is likely to increase with an increase in moisture, organic matter and clay content and reduce with an increase in density. Cricket ball contact with the pitch surface reduces ball energy through friction and energy used (work done) in the deformation of the surface. Reduced plasticity reduces deformation and therefore contact time leading to less energy loss resulting in greater percentage of ball speed retained after impact (James *et al*, 2004). Cricket also requires uniformity of soil deformation across the playing surface.

1.5.2.3 Effective stress and shrink swell

Soil minerals and water are assumed to be uncompressible, unlike the air within the soil. Stress applied to a soil is transmitted through inter-particle contact and this component of stress is referred to as effective stress (σ'). Pore pressure (μ) is the pressure within the fluid in the void space between the soil particles. Terzaghi (1943) defined total stress in terms of these 2 parameters:

$$\sigma' = \sigma - \mu \qquad \textbf{[1.4]}$$

A widely accepted (Lambe & Whitman, 1969) criterion for the measurement of soil ultimate soil failure is Coulomb's equation (1776) using effective stress:

$$\tau = c' + \sigma' \tan \phi' \qquad \textbf{[1.5]}$$

where τ = stress at failure (kPa), c' = apparent cohesion (kPa), σ' = effective stress (kPa) and ϕ' = angle of friction (°).

Soil remains in a state of stress equilibrium until either μ or σ change. Applying a load to saturated soil results in an increase in pore pressure and total stress is balanced by the two internal stress components resulting in no increase in effective stress. For partially saturated soils air and water vapour is considered highly compressible with the presence of air reducing pore pressure (Bishop, 1955). It would therefore follow that a soil with more air voids is likely to be more compressible, for a given soil type, however the force required to compress the soil may increase.

Henkel (1959) confirmed the relationship between water content, soil strength and effective stresses for saturated clays using triaxial compression equipment and reported volume changes at different pore water pressures. Henkel (1960) also showed that the behaviour of clay under any possible loading in the triaxial cell could be determined for both drained and un-drained conditions.

Dissipation of pore pressure through drainage will be dependent on the permeability of the soil and in the case of a low permeability soil (e.g. compacted clay loam) movement of water resulting from a dynamic load would be minimal. Consolidation over time will occur as a result of overburden stress causing the gradual draining of cricket soils within the profile resulting in a natural increase in density with depth. The stress will need to overcome the forces created by the swelling properties of the soil and will therefore be less likely with reduced overburden stress closer to the soil surface. Recovery of consolidated density is not possible without the removal of the stress (Craig, 2004) therefore increasing moisture content through precipitation will not lead to swelling and a reduction in density in cricket pitch soils that have increased density due to overburden stress. However where the soil has been compacted through temporary applied stress in partially saturated soil, water application can cause swelling of clay minerals thus reducing bulk density. Cricket pitches may therefore be in a state of fluctuating density as moisture (through irrigation or precipitation) is applied during the summer followed by rolling and drying; and also a potential swelling over the winter period following a cricket season of rolling. Horn *et al* (1994) states that aggregate strength may also depend on the drying intensity and the number of drying events. He showed that at the same initial bulk density the final aggregate density was higher the larger the number of wetting-drying cycles imposed. Therefore more extreme drying regimes could lead to the need for a greater compactive effort either from roller passes or roller pressure.

DSIR (1951) determined that a sandy clay soil compacted at its optimum moisture (and therefore maximum dry bulk density) would have less air voids than when compacted at a lower moisture and therefore increase density at a quicker rate when dried (due to shrinkage). Smaller volume changes occurred in soils with lower moisture contents. Cricket pitches with a low starting density may therefore shrink and swell less but they could also exhibit lower density and higher moisture contents. This would imply that higher density soils may be more prone to cracking due to the higher volume of expansive mineral content within the profile however the crack dimensions are more relevant to cricket playability than the amount of cracks.

1.5.2.4 Pressure distribution

Boussinesq (1885) determined a theory of stress distribution beneath a point load based on a theory of elasticity. Assumptions for the theory were that the soil was a semi-infinite, homogenous, isotropic mass with a linear (i.e. elastic) stress/strain relationship. Although soils do not comply with these conditions, from a civil engineering viewpoint it is considered that provided stresses are kept well within yield conditions the magnitude of any errors will be small. This may not be the case when predicting stresses in agricultural situations and attempts have been made to predict pressure distribution incorporating soil physical and mechanical parameters.

In its simplest form vertical stress (σ_z) is given by (Sohne, 1958)

$$\sigma_z = \frac{3P}{2\pi Z^2} \qquad [1.6]$$

Where P = Point load (kN) and z (m) is depth below the contact point.

For soil away from the vertical loading axis, Sohne (1958) used polar coordinates adding a parameter for an angle from the load, cos θ (Equation 1.7 and Figure 1.8).

$$\sigma_r = \sigma_1 = \frac{3P}{2\pi Z^2}\cos\theta \qquad [1.7]$$

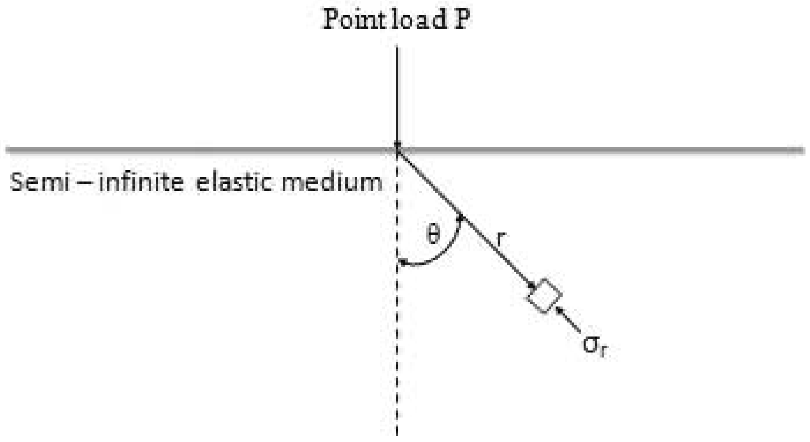


Figure 1.8 Soil stresses due to a vertical point-load (reproduced from Koolen & Kuipers (1983)).

Pressure isobars can be produced from Equation 1.7 which determines the principal radial stress to illustrate stress distribution (Figure 1.9). The depth and extent of the isobars will depend on the load applied.

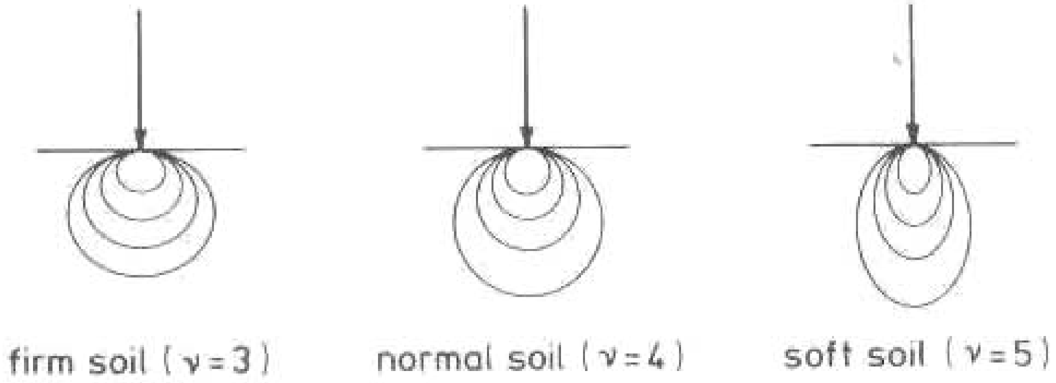


Figure 1.9 Bulb of pressure under point load. ν factor relates to soil hardness where 5 is soft and 3 is hard (reproduced from Koolen & Kuipers (1983)).

The basic expression for vertical stress distribution of Boussinesq, assuming elastic soil behaviour, does not distinguish between soil type or soil conditions and does not take into account soil stiffness or elastic parameters. Attempting to account for this Froelich, 1934 (as cited in Sohne, 1958) suggested an empirical 'concentration factor' *ν*:

$$\sigma_z = \frac{\nu P}{2\pi Z^2} \cos^{\nu-2}\theta \qquad [1.8]$$

and stated that stresses are more concentrated under the load and reach deeper in the soil as ν is greater (Figure 1.9).

Soil loaded through a point load does not represent the situation of a roller contact and other expressions may be more appropriate. Using an adaption of Boussinesq derived by Skempton and Bjerrum (1957) to predict sub soil stresses from a uniformly loaded circular area, Dixon *et al* (2008) characterised stress applied to soil by an athlete running. However using expressions applicable to a uniform strip load may be more appropriate due to the roller length being considerably greater than its breadth. Figure 1.10 illustrates the two dimensional calculations for a strip load.

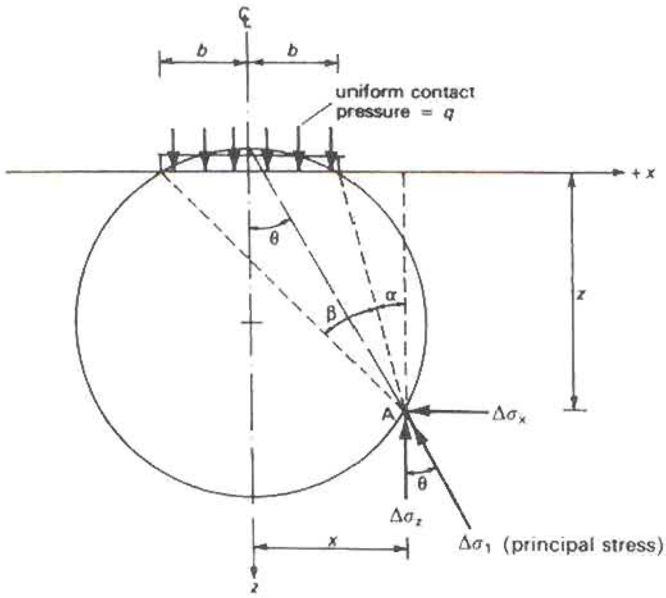


Figure 1.10 Stresses due to a uniform strip load (reproduced from Craig, 2004).

Stresses for a point (z,x) from the centreline are expressed as follows:

$$\Delta\sigma_z=\frac{q}{\pi}\,[\beta+\sin\beta\cos(2\alpha+\beta)] \qquad [1.9]$$

$$\Delta\sigma_x=\frac{q}{\pi}\,[\beta-\sin\beta\cos(2\alpha+\beta)] \qquad [1.10]$$

$$\Delta\tau_{xz}=\frac{q}{\pi}\,[\sin\beta\cos\beta(2\alpha+\beta)] \qquad [1.11]$$

Where q = uniform contact pressure (kPa), angles β and α as per Figure 1.10 (rad). Note that this set of equations does not take into account soil type specific physical parameters.

Theories of plastic failure as opposed to the previously discussed elastic failures are used to estimate load bearing capacity of soil. Crucial to these theories is the heave of soil around the loaded area (not just beneath it) as a structure sinks into the soil. Terzaghi (1943) adapted Prandtl's (1921) original work (that did not take account of soil weight) and added the parameters density, c′ and ϕ′ to the total area of soil in consideration and not just that which was immediately under the loaded area.

Whether plastic theory is applicable to a dynamic load such as a passing roller is not known however the theories do provide an explanation for the increase in surface pressure to a point below the surface before it declines. Terzaghi (1943) derived equations to model pressure under building foundations using soil wedges beneath and to either side of the foundation. Dain Owens (2006) calculated a potential increase in pressure below a 0.17 m^{-2} loaded plate using Terzaghi's equations in an attempt to explain increases in pressure at 250 mm depth compared to surface pressure. The plate was applied to sandy loam soil with a surface pressure of 2.96 bar and pressure at 250 mm was measured at 4.18 bar. Calculations determined that potentially a 14.3 bar pressure could be produced at a depth between 42 mm and 64 mm and it was suggested that a subsequent pressure gradient decline below this depth was the likely scenario.

Bekker (1960) developed sinkage and shear equations from plate sinkage experiments to predict stress under a wheel. This was developed by Onafeko and Reece (1967) who concluded that the Bekker assumption that radial stress beneath a rigid wheel is equal to the pressure beneath strip footing of similar dimensions, was not generally correct. Krick (1969) investigated this in more detail by imbedding pressure transducers into rigid wheels and tyres and measuring normal and tangential stress pressure across the wheel width. Results showed distribution of pressure across the length of the contact was not even and that pressure was slightly greater towards the edges of the rigid roller than in the middle (Figure 1.11). Similar stress distributions were determined for driven and towed rollers however tangential stress was greater for the driven roller and increased with wheel slip due to increased friction at the soil wheel interface.

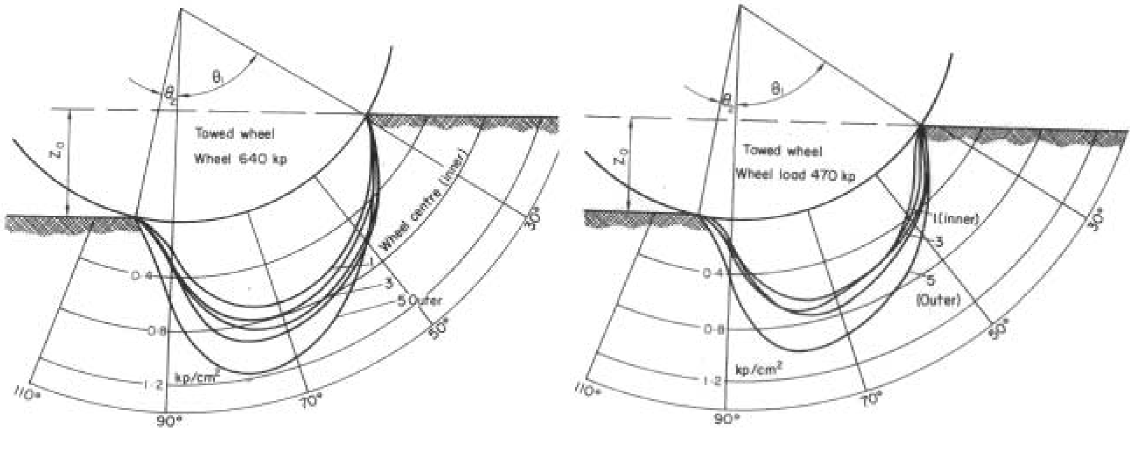


Figure 1.11 Radial stress distribution under a towed rigid wheel with different wheel loading. Curve 1 was taken from the middle of the wheel and working towards the outer edge with curve 5. (Krick, 1969).

Way (1996) employed pressure sensors at depths of 241 mm and 358 mm to determine pressure beneath tyres in a clay hardpan and determined a concentration of pressure behind the central axle. Stress in the soil beneath the roller may therefore be greater than the apparent contact footprint might indicate.

Arvidsson and Keller (2007) measured maximum soil stresses and stress distribution in the topsoil of a 30% clay soil for different wheel loads. They determined that contact stress calculated from the contact area on a hard surface was close to the tyre inflation pressure, however the measured maximum vertical soil stress at 10 cm depth was generally higher than the contact stress and on average it was 39% higher at an inflation pressure of 100 kPa.

Mathematical modelling of soil and tyre interactions and soil stresses beneath a wheel using finite element methods (FEM) (Fervers, 2004; Liu & Wong, 1996; Raper *et al*, 1995; Yong *et al*, 1978) and discrete element methods (DEM) (Asaf *et al*, 2006) enable the prediction of subsoil behaviour, however this complex methodology is beyond the scope of this project.

1.5.2.5 Particle movement

Soil movement resulting from a dynamic load by a smooth wheeled roller was investigated by Wong (Wong, 1967; Wong & Reece, 1967a; Wong & Reece, 1967b) using a glass-sided box that enabled soil flow to be photographed during roller movement. At a slow roller speed (0.065 km h^{-1}) long exposure (20 s) photographs were taken of white talcum powder dots to investigate the dot trajectories in a clay soil (41.8% volumetric moisture content and a bulk density of 1.74 g cm^{-3}, (equating to a dry bulk density of 1.32 g cm^{-3} at 32% gravimetric moisture content. This technique showed two-way longitudinal soil movement as well as two-way vertical movement. This technique was used for towed as well as driven wheels and indicated the different particle movement with roller type as well as with depth (Figure 1.12) for an uncompressible soil.

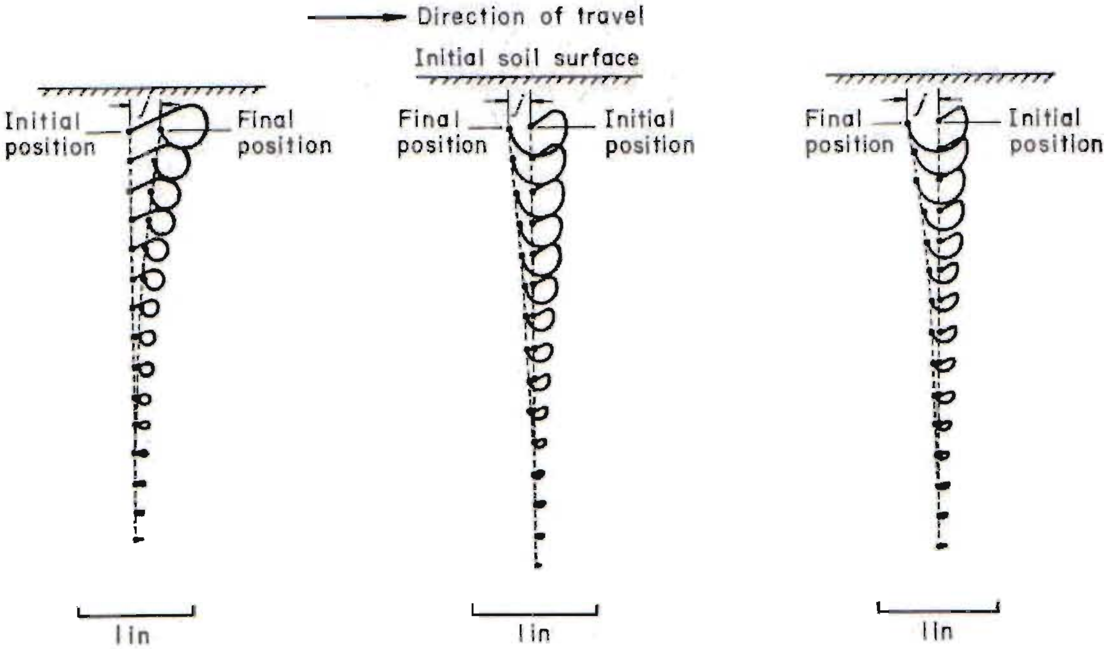


Figure 1.12 Photographically determined trajectories of the particles and shear displacements in clay beneath a roller for towed (left), driven (centre), driven 63% slip (right) (Wong, 1967).

It was noted that the final positions of the particles for a towed roller were in front of their initial positions and for a driven roller they were behind and Wong concluded the final displacement is an indication of the net horizontal force applied to the soil and therefore for the towed roller the horizontal force is greater and transmitted to the soil by the roller.

Wong describes two separate flow patterns (Figure 1.12) and states that the trajectories indicate a state of Rankine passive failure (Rankine, 1857) immediately in front of a moving roller.

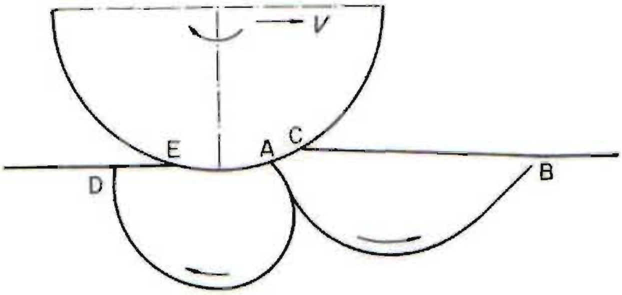
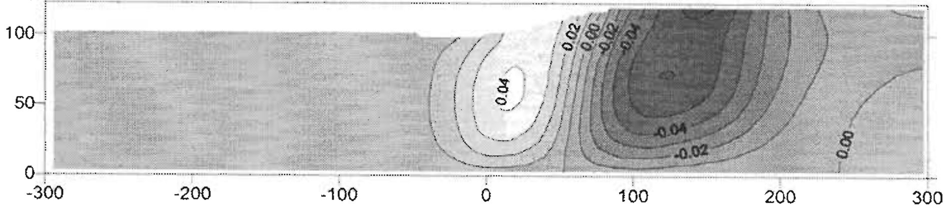


Figure 1.13 Photographically determined flow patterns in clay beneath a towed roller. 2 separate flow regions A,B,C and A,D,E. V = direction of movement (Wong, 1967).

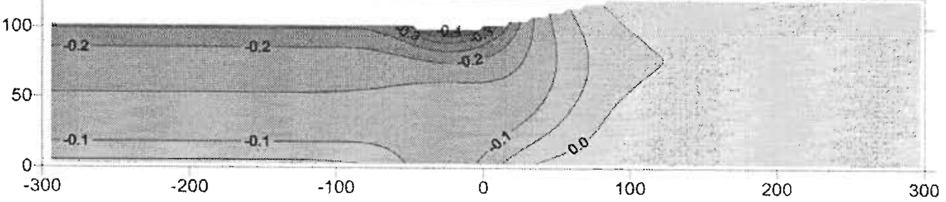
In conclusion, Wong suggests that using plate sinkage methods to predict soil movement did not account for the longitudinal flow. This work provides evidence of soil particle movement in a saturated clay soil but does not investigate compaction of unsaturated soils and also does not investigate differences between moisture content and roller parameters.

From analysis of marker movement during rolling Maciejewski *et al* (2004) (see Section 1.5.3.1) were able to generate a series of two dimensional strain distribution graphs (Figure 1.14).

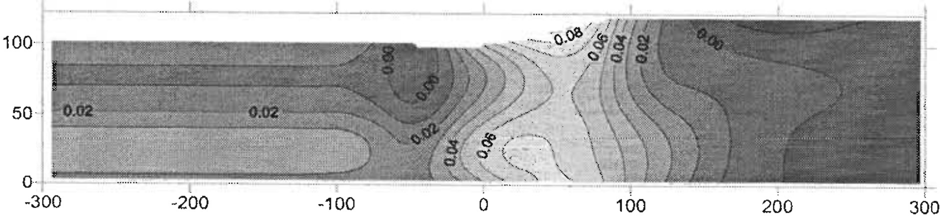
(a) horizontal strain



(b) vertical strain



(c) shear strain



(d) density

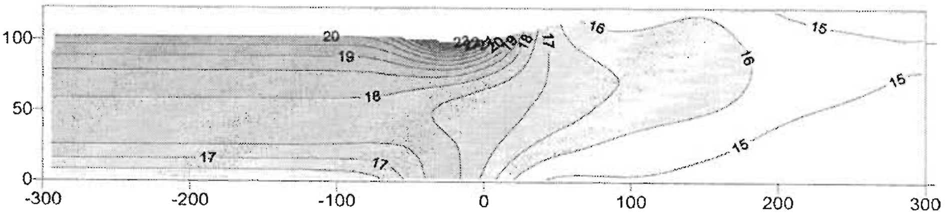


Figure 1.14 Strain and density distribution from a 340 kg m^{-1} rigid roller measured from particle movement observed in photographic images. Maciejewski and Jarzebowski (2004).

Particle movement was determined to take a similar 2 dimensional movement as described by Wong (1967).

Shikanai *et al* (2000) used a similar photographic set up to Maciejewski and Jarzebowski but magnified the images 60 times to increase accuracy of measurement of the polyester film markers. Particle movement was similar to previous studies but the accuracy of measurement was greater. However the aim of this study was to ascertain wheel slip parameters on a sandy soil and therefore the results have limited relevance to this project.

1.5.3 Rolling and rollers

Research specifically to determine roller efficiency has previously been aimed at the construction industry for infill compaction or for road and airfield construction. No research specifically for compaction of cricket soils in the UK has been documented although Adams and Stewart (1968) suggested 'final stages of consolidation are not achieved by rolling, and could not be, for the force required is too great. It is a product of the cohesion of water in small pores acting on the soil particles with which it is in contact when evaporation takes place'.

1.5.3.1 Roller passes

The Road Research Laboratory (DSIR, 1951) published details of laboratory studies on compaction of a variety of 'loose' packed soil types using smooth-wheeled rollers. They showed that rolling effectiveness declines with each roller pass and considerably so after 8-10 passes at an optimum moisture content derived from the standard BS compaction test (Proctor test, (Proctor, 1933) see Section 1.4.3.4) (Figure 1.15).

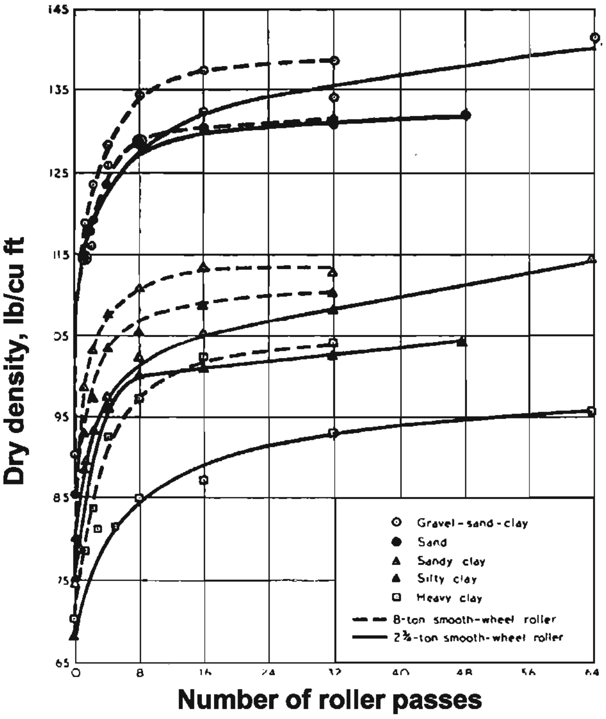


Figure 1.15 Relationships between dry density and number of passes of the 8 ton (7.25 t) and 2.75 ton (2.5 t) smooth-wheeled rollers for five different soils when compacted in 9 inch (228.6 mm) loose layers at or just above their optimum moisture contents for roller compaction (reproduced from DSIR 1951); (100 lb/cu ft = 1.602 g cm^{-3}; 1 ton (imp) = 0.91 t (met)).

It was noted however that density continues to increase, albeit at a slow rate, to in excess of 60 roller passes and it was assumed that this was a result of increasing pressure due to a reduction in contact area. It was felt however that ‘the small increase (after 8 passes) was not justified economically’. Sandy clay (Figure 1.15) (25% clay. 35% silt, 40% sand) achieved a maximum density of approximately 1.68 g cm^{-3} after 16 passes for the 2.75 ton (2.5 t) roller and 1.80 g cm^{-3} for an 8 ton (7.25 t) roller (Figure 1.16), indicating the large increase in force required to compact high density soils.

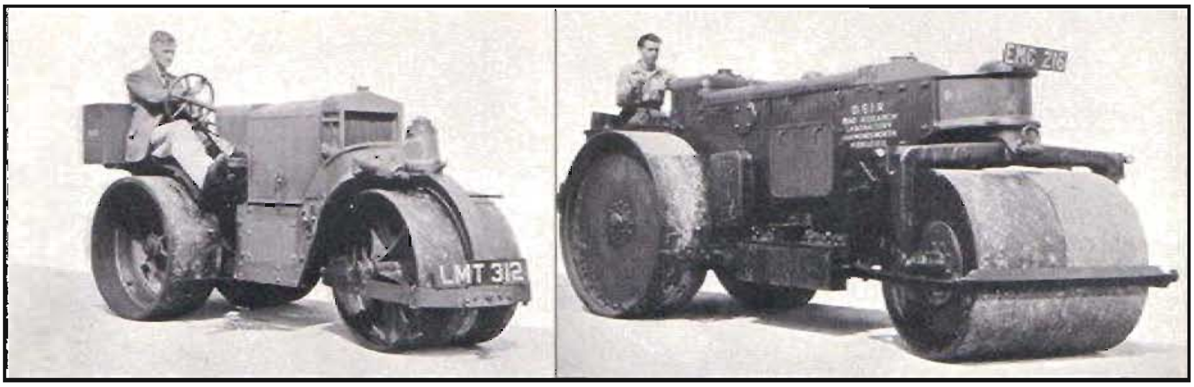


Figure 1.16 2.75 ton and 8 ton rollers used for DSIR rolling experiments (DSIR 1951).

Comparison of rollers calculating $\frac{\text{Roller weight}}{\text{Total roller width}}$ was not considered to give as good an indication of performance as a calculated value that also took into account roller diameter termed Roller effect:

$$\text{Roller effect} = \frac{\text{Load on roller (kg)}}{\text{width of roller (m) x diameter of roller (m)}}$$

This calculation, which is still used in some texts, is useful as a comparison between rollers, particularly when investigating the compaction potential of differing drum sizes and weights on the same roller (Figure 1.15). However no difference between front and rear roller compaction was determined despite large differences in this number for the rollers in Figure 1.16.

The DSIR (1951) showed that a reduction in maximum density occurred when soil was compacted at higher or lower moisture than the Proctor optimum however the soils with moistures above the optimum reached their maximum with fewer roller passes. They also determined that the standard BS compaction test (see Section 4.2.2) gave a good correlation with maximum density achieved with both of the rollers used and they also identified a similar relationship to a Proctor curve by using the roller at different moisture contents to identify an optimum moisture content. Tests indicated that maximum density was consistently at approximately 5% air voids.

All data from the DSIR (1951) were intended for the construction of roads and airfields and so they used loose soil. Rapid increases in density would therefore be likely for initial passes and roller pass results would not be appropriate for cricket pitches already at a reasonable level of compaction. Rollers used in this work were also heavier and narrower than those currently recommended for cricket. This initial review of the work makes no mention of depth of compaction but it was stated that ‘the depth of the layer compacted depends on the weight of the roller’.

Parsons (Parsons, 1992) in his review of all the work performed at the Transport Research Laboratory, Berkshire, UK (formerly DSIR) regarding compaction expressed compaction in terms of a relative compaction percentage. This is the percentage of the maximum density achieved in a standard BS compaction test (2.5 kg rammer) i.e. Proctor test. Figure 1.17 presents the results for roller passes in the sandy clay (as in DSIR (1951) above) for the relationship between the standard compaction test and the consequence of compaction either side of the predicted optimum moisture. 10 – 16 passes (of a 2 drum/twin axle roller) were required to reach 100% relative compaction and up to 32 passes were needed until maximum density on a sandy clay soil was achieved (105% relative compaction).

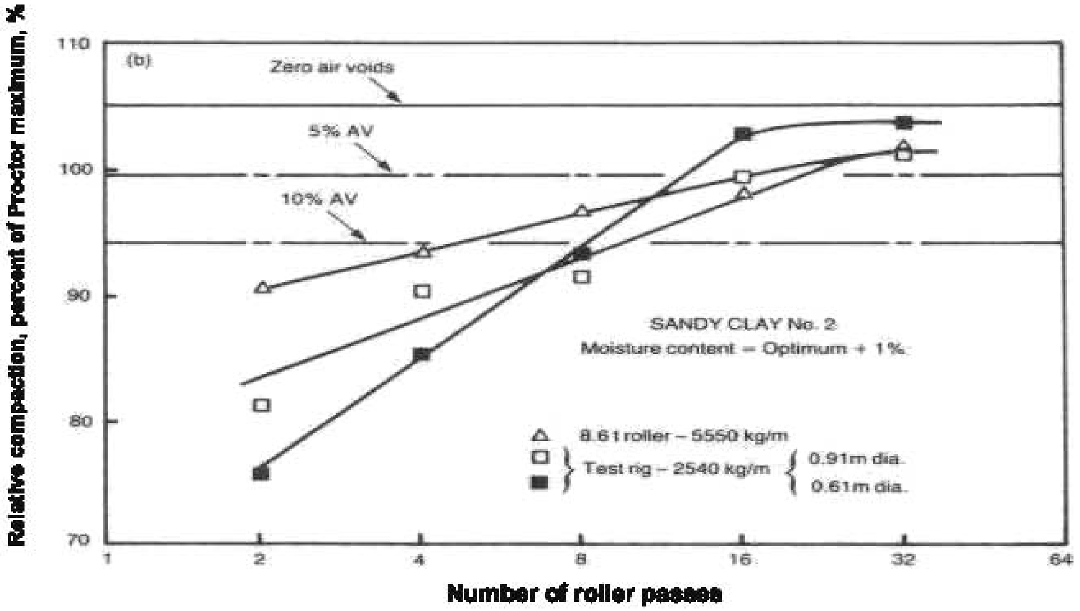


Figure 1.17 Relations between relative compaction and number of passes of smooth-wheeled rollers on sandy clay at three different values of moisture content and a soil profile depth of 150 mm. Values related to the maximum density and optimum moisture obtained from a 2.5 kg rammer (reproduced from Parsons, 1992).

When using this in a cricket context it should be noted that starting density in cricket is generally at dry densities >1.40 g cm^{-3}, which will be shown later in this thesis to be approximately 85% of Proctor optimum density, and that the rollers used for this work were much heavier than those used in cricket but the general conclusions reached by Parsons (1992) are important for this project.

The results from Parsons (1992) (Figure 1.18) provide a basis for determining potential roller compaction in cricket pitches but fall short in a number of areas. In particular the experiments did not incorporate grass into the soil profile and the soils had clay contents above or below the standard cricket soils clay contents. In addition cricket rollers are in general less than 1000 kg m^{-1} for which the Parsons data is limited, however in the 500 to 1250 kg m^{-1} roller mass range the data suggests that an optimum dry bulk density of 85% – 90% of Proctor optimum density would be achievable.

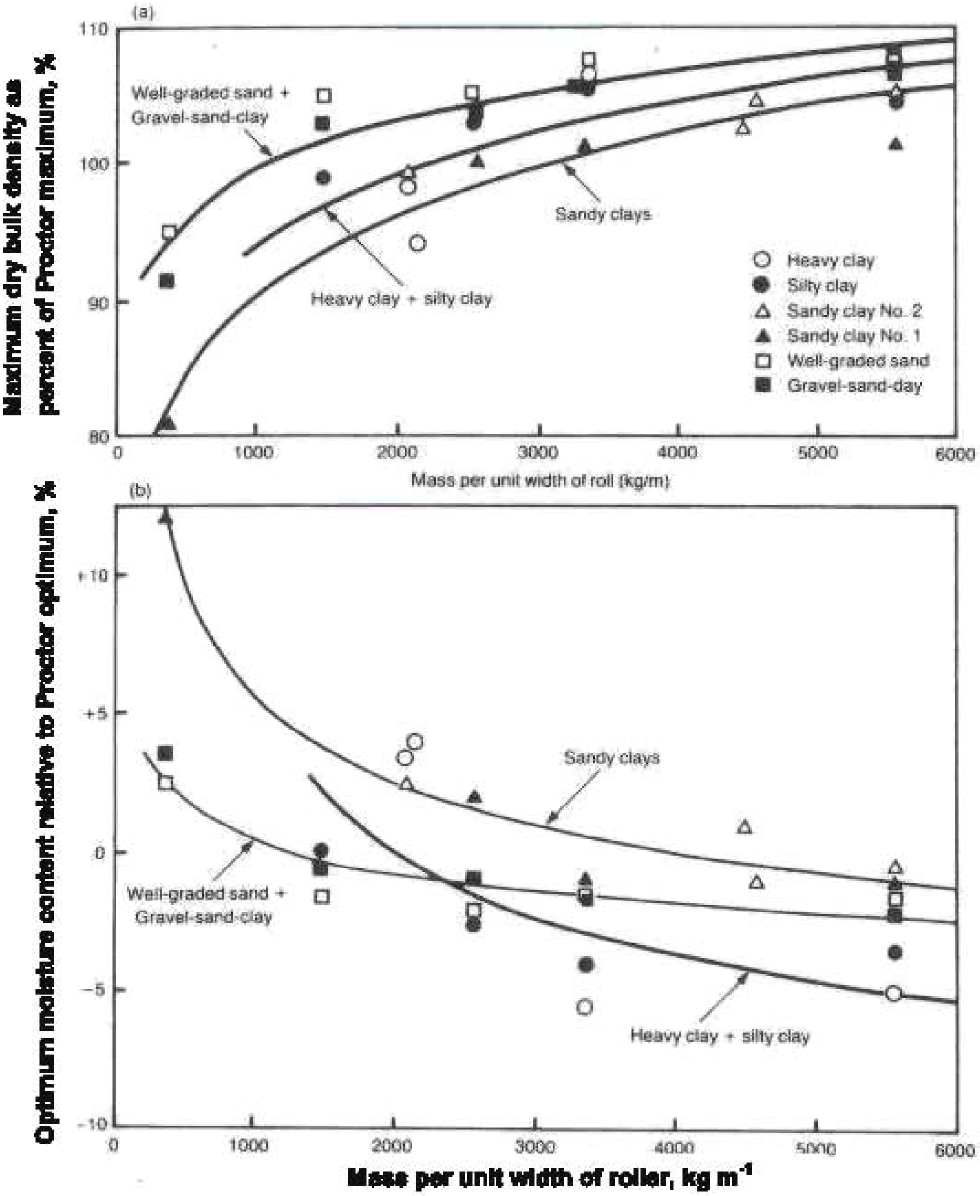


Figure 1.18 Maximum dry bulk densities and optimum moisture related to the mass per unit width of smooth-wheeled rollers (reproduced from Parsons 1992).

The level of compaction at any given number of passes increases with an increase in mass per unit width of roller. The optimum moisture required also reduces to enable the increase in achievable density. For a sandy clay the optimum moisture contents were found to be above Proctor optimum at the lower roller mass per unit width and as the moisture content is increased, the number of passes to achieve a given level of compaction is reduced (Figure 1.19). Optimum moisture was shown to reduce with mass per unit width of roller but current cricket roller weights fall below the scope of this data.

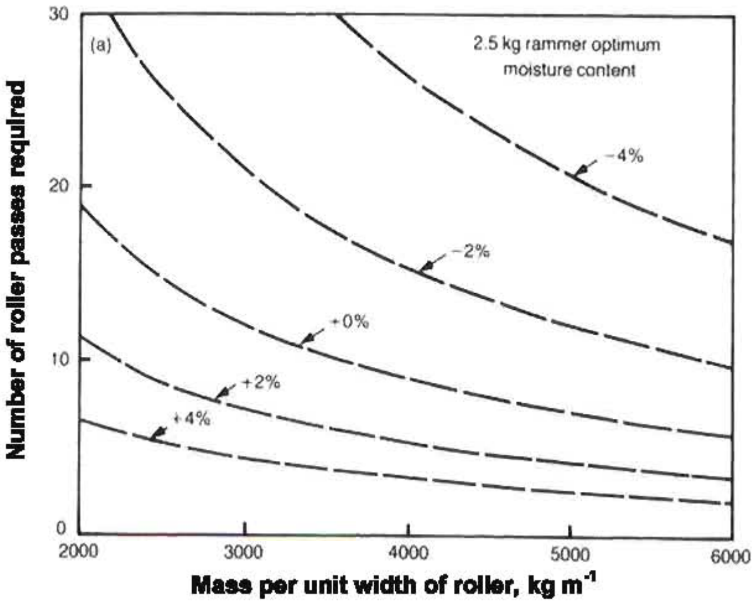


Figure 1.19 Smooth-wheeled rollers on sandy clay. Relation between the number of roller passes required and mass per unit width of roller to achieve 95% of maximum Proctor density obtained in a standard BS compaction test (Parsons 1992).

Some other notable conclusions presented by Parsons (1992) are as follows:

- Depth of compaction achievable (90% of maximum density) was determined as approximately 50 mm for a load of 500 kg m^{-1} to 150 mm with 1500 kg m^{-1} on sandy clay soil
- Roller diameter is a function of its weight so performance can be related to mass per unit width of roller
- Roller speed increased roller passes required to reach maximum bulk density but by a negligible amount in the cricket speed range (0.3-1.0 km h^{-1})

The Department of Transport (Department of Transport, 2006) has incorporated the work of the Transport Research Laboratory into the specification for highway works and the standard for cohesive fill is 8 passes (or 100% of maximum dry density or 5% air voids) with a minimum mass per metre width of 2100 kg m^{-1} to compact to a depth of 125 mm.

From an agricultural perspective it has been suggested that the first pass of a wheeled vehicle causes 50% of compaction, the second another 10%, the third a further 6% and the fourth a further 3% (NSRI, 2001). No further detail was provided on the nature of the load and wheel dimensions. Raghaven *et al* (1976) evaluated compaction under various soil and vehicle parameters and concluded that density increased sharply up to five passes and levelled off for further passes.

Assessing the affect of multiple passes of a rigid wheel Abebe *et al* (1989) measured rolling resistance, surface sinkage and compaction on a sandy loam soil that was compacted at 1.20 g cm^{-3} in a 0.4 m wide soil bin using a roller producing up to 600 N (153 kg m^{-1}) of force. They concluded that 'the largest part of the compaction process occurred during the first 3 passes of a loaded wheel' and that maximum bulk densities were normally achieved after 6 passes.

Maciejewski and Jarzebowski (2004) analysed soil deformation below a rigid roller in a material designed to simulate cohesive soil using a soil bin with a transparent wall. Markers were placed in the soil which and were photographed before and once during roller movement. From analysis of marker movement vertical and horizontal displacement was determined and effective compaction calculated. They concluded that the major compactive effect was achieved after the first pass and was smaller for each subsequent pass and the single pass of a heavy roller (3000 N; 508 kg m^{-1}) compaction was higher than repeated cycles of a light roller (600 N; 102 kg m^{-1}). No statistical increase in density occurred after 6 passes. Maciejewski's work did not involve any assessment of the effect of different soil moisture contents.

Using the same equipment as Maciejewski *et al* (2004) Jarzebowski *et al* (1998) observed that during towed roller tests (passive), parallel cracking was observed behind the roller. They determined that the depth and distance between cracks increased with an increasing roller weight. No cracks occurred below a light roller (500N; 85 kg m^{-1}) and all cracks closed after 4 passes of the roller as vertical displacement increased.

1.5.4 Grass roots and soil strength

The strength and playability parameters of the cricket pitch are affected by the grass grown on the playing surface and the grass roots within the soil profile; however managing the high dry bulk density rootzone to support healthy grass growth provides a challenge to the cricket groundsman. In the UK, *Lolium perenne* varieties are required to root through the compacted soil to depths greater than 100 mm. Autumn grass establishment is commonly accompanied by decompaction of the rootzone with the intention of improving grass root development but at the expense of soil dry bulk density which then requires re-compaction the following spring. No upper limit of dry bulk density for the successful establishment of autumn sown seed on cricket soils has been previously established.

1.5.4.1 Soil-plant interaction in compacted cricket soils

The root growth and root distribution of crop plants has also been shown to change as a result of compaction (Van Ouwekerk & Van Noordwijk, 1991) and compensatory growth in less compacted levels in a soil profile can occur in some crops (Mulholland *et al*, 1999) although different crops show different sensitivity to compactness. McGowan *et al* (2008) showed that a greater rootmass occurred in low porosity soil near to the surface, compared to high porosity soil, as a response to greater inter-species competition for rooting space and nutrient and moisture uptake in *Agrostis palustris.*

Tardieu, (1988) using three-dimensional mapping of root distribution, showed that high levels of compaction at the plough layer proved an obstacle to root penetration in wheat (*Triticum aestivum*) and can cause a reduction in rootmass density. Cricket pitch preparation is concerned with removal of moisture to a depth in excess of 100 mm whilst maintaining grass health. Reduced rootmass and root penetration reduces the depth and speed of moisture removal and this could affect pitch playability characteristics.

Plant roots affect the soil structure and as a result can alter the water retention characteristics of the rhizosphere soil. Rooting has been shown to increase the amount of larger pores resulting in greater drainage potential (Whalley *et al*, 2005). The growth of roots into compacted soil has also been shown to reduce porosity (Dexter, 1987) as root volume is accommodated by loss of porosity.

Soil compaction directly affects the system of macropores and, therefore, primarily the soil physical root growth factors i.e. water, aeration, mechanical resistance and temperature. This change in soil physical environment may affect specific biological and chemical properties, such as the availability of nitrogen (Boone, 1988).

Baker *et al* (1998b) determined differences in rootmass density in seven different cricket loams used in experimental cricket pitch profiles in particular in the top 100 mm of the soil profile. In conclusion they suggested that root density appeared to be related to organic matter and bulk density but offered no explanation for this.

1.5.4.2 Soil compaction, root strength and root penetration

The contribution of grass roots to the strength of the profile may increase the force required to compact the soil as the interaction of grass roots on soil has been shown to increase soil strength. Tengbeh (1993) showed that grass roots increased ‘considerably’ the magnitude of soil strength in two soil types by using a hand held shear vane to test soil strength. Van Wijk (1983) compared playing conditions in the field and the laboratory and concluded that ‘grass roots must contribute considerably to the penetration resistance of the turf’. This work found the contribution of grass roots to soil strength was in the order of 0.8-1.6 MPa and considered that this was due to the high root densities in the top 25mm of rootzone.

Adams *et al* (1985) showed a positive correlation between shear resistance and ash-free root weight, as well as a clear relationship between root strength and root diameter in six turfgrass cultivars. Shipton (2004) confirmed this correlation but also showed that soil moisture content affected root distribution and root strength.

As well as the turf plant matrix of interlocking roots affecting the soils shearing resistance, the production of mucilage from roots, in particular from root hairs, enhances the ability of roots to attach to soil particles (Huang, 2000).

It is apparent that approximately 3 MPa or more of penetration resistance (PR) will begin to inhibit root penetration and crop growth. Montagu *et al* (2007) showed compensatory root growth for a broccoli (*Brassica oleracea*) crop in the topsoil overlying a compacted subsoil that had a PR of 3.1 MPa. Sadras *et al* (2005) experimenting with wheat (*Triticum aestivum*) in Australia showed a range of root growth and yield reduction as a result of compacted subsoils in sandy loams with a PR up to 3 MPa. Coelho *et al* (2000) examining the response of cotton (*Gossypium* sp.) growing in a eutric fluvisol in Spain showed reduced rooting through a subsoil with a PR >3 MPa and a reduction in crop growth. Dexter (1986c) showed that the proportion of roots penetrating a compacted subsoil under a tilled seedbed decreased exponentially with subsoil strength in wheat plants and concluded that PR should not exceed 0.4 MPa for dicotyledonous plants and 3 MPa for monocots (which include grasses). Chan *et al* (2006) showed no decline in yield of a wheat crop (monocotyledon) grown in soil with a dry bulk density of 1.58 g cm^{-3} (PR >2 MPa) compared to 1.25 g cm^{-3} (1 MPa PR) but determined a 66% decrease in yield of canola (*Brassica napus/rapa*, dicotyledon) under similar conditions.

Soil type, moisture, bulk density and organic matter combine to influence PR. Aggarwal (2006) researched this relationship in a sandy loam soil growing wheat and concluded that soil water content alone accounted for 59% variation in PR and with bulk density accounted for 93–96% of the variation. The effect of moisture content on PR was investigated by Van Wijk (1983) who determined that a large increase in penetration resistance from 0.4 MPa to 3.8 MPa occurred below 20% moisture for a soil with 17% clay at 1.66 g cm^{-3} dry bulk density.

Using a prediction model of soil PR (Dexter *et al*, 2007), measurements of resistance in clay loam soils with a clay content of approximately 30% would be predicted to be >3 MPa at approximately 1.75 g cm^{-3} when the soil was at 10 kPa tension suggesting a limit to root penetration could occur in highly compacted cricket soils (Figure 1.20). However for a moisture content of less than 20% gravimetric moisture content a large increase in PR may be anticipated.

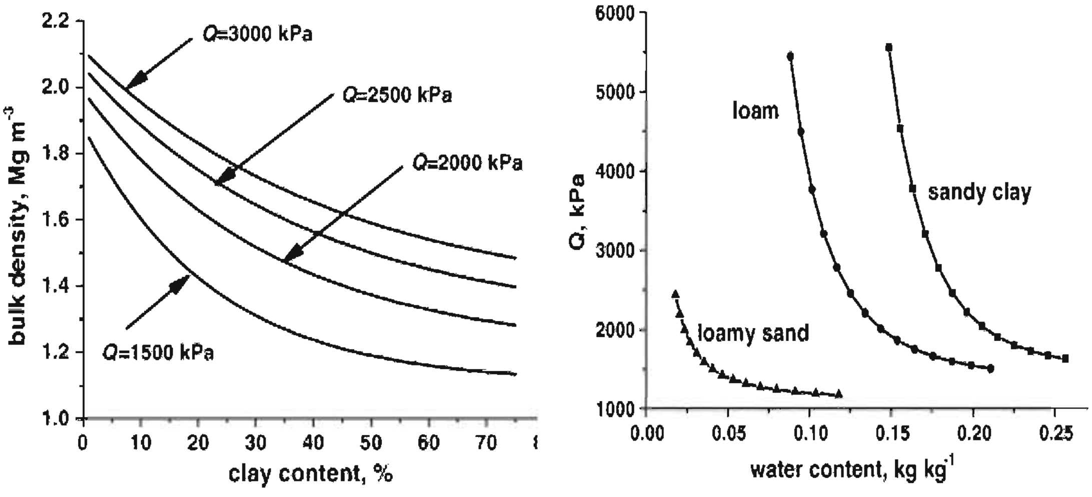


Figure 1.20 Values of bulk density (ρ_d) for different values of soil clay content that are predicted to give various values of penetration resistance, *Q*, at a soil water suction of *h* = 100 hPa (10 kPa) (left). Predictions of how penetrometer resistance, Q, varies with gravimetric water content, θ, for three soil texture classes (right) (reproduced from Dexter el al, 2007).

Ekwue *et al* (2006) showed penetration resistance in compacted high clay (up to 80%) Trinidadian cricket loams ranged from 2.21 to 6.44 MPa depending on the level of compaction and the moisture content.

Apart from soil strength, soil cracks and biopores determine the penetrability of the soil to roots (Dexter, 1986a; Dexter, 1986b). Biopores (created mainly by roots and earthworms) add significantly to root penetration at depth, even when the content of small, vertical pores is only 0.1% (v/v) (Jakobsen & Dexter, 1988) but constant compaction of the cricket pitch in the top 100 mm reduces opportunities for these macropores to persist.

1.5.4.3 Grass growth response to compaction and moisture removal

Cricket pitch grass is not grown for yield but as a mechanism to facilitate moisture removal from the pitch profile. Grass leaf growth on the playing surface also influences ball-surface interactions. Although yield is not a determinant of pitch performance leaf and root growth is affected by the uptake of water, oxygen and nutrients which in turn are dependent on the size (length) of the root system and on soil physical parameters (Boone & Veen, 1994). Moisture removal from the pitch profile through evapotranspiration is a necessary process for the even drying of the pitch soil profile, to achieve optimum hardness of the surface and also to increase dry bulk density through shrinkage (Adams *et al*, 2001; Baker *et al*, 1998b).

In terms of moisture removal from the cricket pitch soil profile root size and grass moisture demand are therefore the determinants and the depth of the root will determine where the moisture is removed from. The rate of water supply from the soil to a root depends on the difference in water potential between the root and the soil, the conductivity of water in the soil around the root and the soil-root contact. In a compacted soil these parameters are generally favourable. Hydraulic conductivity reduces with compaction and affects the movement of moisture to the grass root however an increase in capillary rise and subsequent evaporation could occur.

1.5.5 Summary of relevant knowledge

Correct rolling management for cricket pitch preparation has not been established. No official recommendations in the cricket industry currently exist for the use of a smooth-wheeled roller to increase bulk density in terms of roller parameters and soil conditions. Rolling management is largely based on hearsay and anecdotal evidence and varies throughout the industry but the extent of variation has not been established. Likewise the variation in soil type and machinery availability is not known.

Critical to this research is what parameters affect pitch playability and to what extent they can be measured. A consensus of work would indicate dry bulk density, moisture, organic matter and possibly clay content to be influential in playing surface performance. Rolling of the pitch would be expected to increase dry bulk density however the relationship between moisture and increasing bulk density is crucial to rolling dynamics as well as playability and has not been established for cricket soils and cricket pitch management.

Target densities, moistures and organic matter have been defined and these provide a benchmark for groundsmen preparing cricket pitches as well as for experimental work. As a means to measure playability the Clegg hammer and ball rebound are currently considered adequate predictors of bounce but not actual pace.

It has been shown that the potential to compact reduces with the number of repetitive passes both experimentally and in practice and that load variation affects the extent of change in bulk density. The actual weight, speed and diameter of rollers relevant to cricket pitches have not been assessed previously and neither has the effectiveness with regard to changes in soil moisture.

A well documented understanding of soil compaction already exists and fundamental stress strain relationships have been established. Standard laboratory Proctor tests have been shown to be adequate predictors of dry bulk density potential within the range of rollers used in cricket.

Theoretical pressure distribution beneath a load can be calculated in a number of ways principally derived from static load situations. They reflect a basic understanding that increased load will increase the degree of pressure as well as the depth to which the pressure will extend. Linking increase dry bulk density to pressure has been modelled but no universal relationship has been established particularly with regard to changing soil mechanical and physical parameters. Pressure has been shown to vary across the length of the soil/roller interface as well as across the width of the roller. This makes the prediction of soil pressure from a visual roller contact measurement unreliable.

Soil movement under a dynamic load has been analysed but with different soil physical and mechanical conditions than would be found in cricket pitches. Comparisons between soil moisture conditions have not been documented and neither have differences in roller diameter and speed that are appropriate to cricket.

Grass roots affect the strength characteristics of the soil profile. Compaction of soil changes the root environment affecting the rooting and growth characteristics of plants and influencing root distribution. For monocotyledonous plants such as grass it has been demonstrated that a soil penetration resistance greater than 3MPa will reduce root penetration. This is a condition that could potentially exist in a cricket pitch profile and may indicate an upper limit for target dry bulk density. Moisture removal from the cricket pitch profile will depend on the growth of the plant and the plants rootmass. Where the moisture is removed from will depend on the location of the roots. No published data for rooting into compacted cricket soil was found.

The areas where little or no knowledge exist were identified from the outset of the project and provided the basis for the experimental design. The objectives of this thesis are derived from these unknowns and are detailed in the next chapter.

Chapter 2. Project focus, aims, objectives and hypotheses

2.1 Identified knowledge gaps

The previous chapter established a number of weaknesses in current knowledge regarding cricket pitch rolling management and these are the focus of this thesis. The following list highlights the main areas for investigation:

1. The extent of the variation in rolling management between venues and groundsmen needs to be clarified. Pitch drying and rolling between venues will vary according to soil type and climatic conditions as well as equipment and labour availability. A better understanding of current practice will establish the need for further research, inform experimental design and enable the need and targeting of guidelines.
2. Practical issues relating to rolling practice need to be established. These can be classified into 3 categories:

    1. *When* – the timing of rolling use with regard to soil moisture content
    2. *What* – the roller design parameters appropriate to achieve the desired dry bulk density change
    3. *How* – the number of roller passes and the speed of operation required to achieve the desired outcome

    These are the main operating parameters for cricket pitch rolling and will enable the generation of guidelines.
3. The relationship between the moisture, pressure and increasing bulk density needs to be developed in a cricket context. The existing knowledge is not specific to cricket in terms of roller weights and the inclusion of grass roots into a highly compacted clay loam soil. Soil physical and mechanical parameters affect the required pressure to achieve compaction. The efficiency of compaction will depend on matching roller pressure to optimum soil physical conditions. An improved awareness of this relationship will inform a groundsman's roller choice and timing decisions.

4. Grass plants and their roots have an important function in cricket pitch preparation and performance. An even establishment and growth in a compacted clay loam profile is required for soil moisture removal. An upper limit for soil bulk density would be marked by poor root penetration. Root distribution within the profile will affect the soil drying process which is crucial to pitch preparation. Even drying of the profile is a factor in consistency of playability factors. Work needs to be undertaken to improve the knowledge of rooting into compacted soils which will make a significant contribution to cricket pitch management.
5. Soil movement underneath a dynamic load has been characterised but soil movement with different soil moistures and with different roller diameters and roller speed for cricket has not been researched. Development of this is necessary to increase the scientific understanding of soil movement under a dynamic load and to determine potential damage caused by rolling in inappropriate soil physical conditions.

2.2 Research questions and hypotheses

1. Current practice is a result of experience and anecdotal evidence but the extent of variation in rolling management is unknown. The need for guidelines has to be established as the assumption of the sponsors is that widespread variation in rolling practice results in variable pitch quality between venues. Limited variation within the pitch resulting from non uniform bulk density and moisture is, to a certain extent, acceptable as the complete removal of variation detracts from the game of cricket.
2. Cricket soils vary in their physical and mechanical properties and the extent of this variation has been established. Mechanical parameters (stiffness, elasticity) with regard to changes in moisture have not been studied for cricket loams and this thesis has a working hypothesis that soil mechanical properties change in relation to the soil moisture content and bulk density thereby affecting the load required for compaction.
3. Optimum moisture has been shown to differ between different compactive loads resulting from the relationship between air voids, moisture content and bulk

density. The incompressibility of water prevents any increase in bulk density at soil saturation and therefore soil compaction can only occur when air voids are present. The extent to which an increase in air voids requires a greater compactive pressure to instigate soil compaction needs to be established for cricket soils, hypothesising that an increase in air voids above an optimum level requires an increase in compactive pressure to increase bulk density.

4. Successive roller passes have a decreasing effect on increasing dry bulk density for a given load and soil physical conditions as determined by DSIR (1951) and others. The extent of this reduced dry bulk density increase needs to be established for cricket soils and at levels of dry bulk density commonly found in cricket pitches.
5. Roller speed affects compaction but work determining this (DSIR, 1951) did not cover speeds relevant to cricket pitch preparation. The project hypothesises that an increase in roller speed will reduce the increase in dry bulk density.
6. Increasing the load applied to soil leads to an increase in bulk density. The extent to which roller weight can increase bulk density for a given soil physical condition needs to be established for cricket soils.
7. Grass roots have been shown to have a reduced penetration in soils with a PR greater than 3 MPa and this is likely to occur at the upper end of dry bulk density levels associated with cricket pitches under certain soil moisture conditions. Soil moisture reduces penetration friction and therefore reduces PR. The working hypothesis for grass root penetration is that high levels of soil compaction will increase PR in cricket soils and result in a reduction in the depth of root penetration.
8. Soil movement under a dynamic rigid roller has been shown to be a two way movement both vertically and horizontally (Wong, 1967). It has also known that soil mechanical properties alter with soil moisture. The extent of soil movement with regard to changes in soil moisture needs to be established for cricket soils to determine potential soil physical damage from rolling in inappropriate rolling conditions, the working hypothesis being that increases in soil moisture result in greater soil movement due to increases in elastic properties.

2.3 Research aim

Encompassing the focus of the project and the research questions the research aim is:

To develop an improved understanding of the compaction of cricket soils under a dynamic compressive load in order to provide practical strategies and guidelines for the optimisation of cricket pitch compaction by rolling.

2.4 Research objectives

In order to achieve the project aims this thesis has the following objectives:

1. To determine current cricket pitch rolling management practice in the UK for all levels of the game through a survey of cricket groundsmen.
2. To determine soil mechanical properties and the strength and failure mechanisms of commonly used cricket loam soils when subjected to compaction under controlled laboratory conditions
3. To determine the relationship between optimum soil physical conditions and cricket roller pressure to maximise rolling efficiency.
4. To determine efficient rolling protocols for pitch preparation in terms of soil moisture, roller weight, roller speed and roller diameter through field and controlled environment experimentation.
5. To investigate the effect of soil compaction on grass rootmass and its distribution in order to determine limitations to compaction bulk density resulting from rolling management.
6. To characterise and quantify the dynamic forces that occur during rolling and determine any differences in force environments between roller weight, roller diameter and soil moisture.
7. To provide practical guidelines for efficient rolling management protocols and issues related to rollers and for operating parameters.
8. To determine benefits of the project to the sponsors business model and to assess potential financial and environmental benefits from any proposed change in rolling management.

2.5 Project approach

The project objectives cover a range of fields of study necessitating a similarly wide mixture of methodology. Figure 2.1 outlines the connections between parameters to be examined, properties to be assessed, experiments undertaken, and the objectives of the thesis. Objective 7 (rolling optimisation guidelines) is achieved from the results of objectives 1-6 and informs Objective 8 (benefits to the ECB).

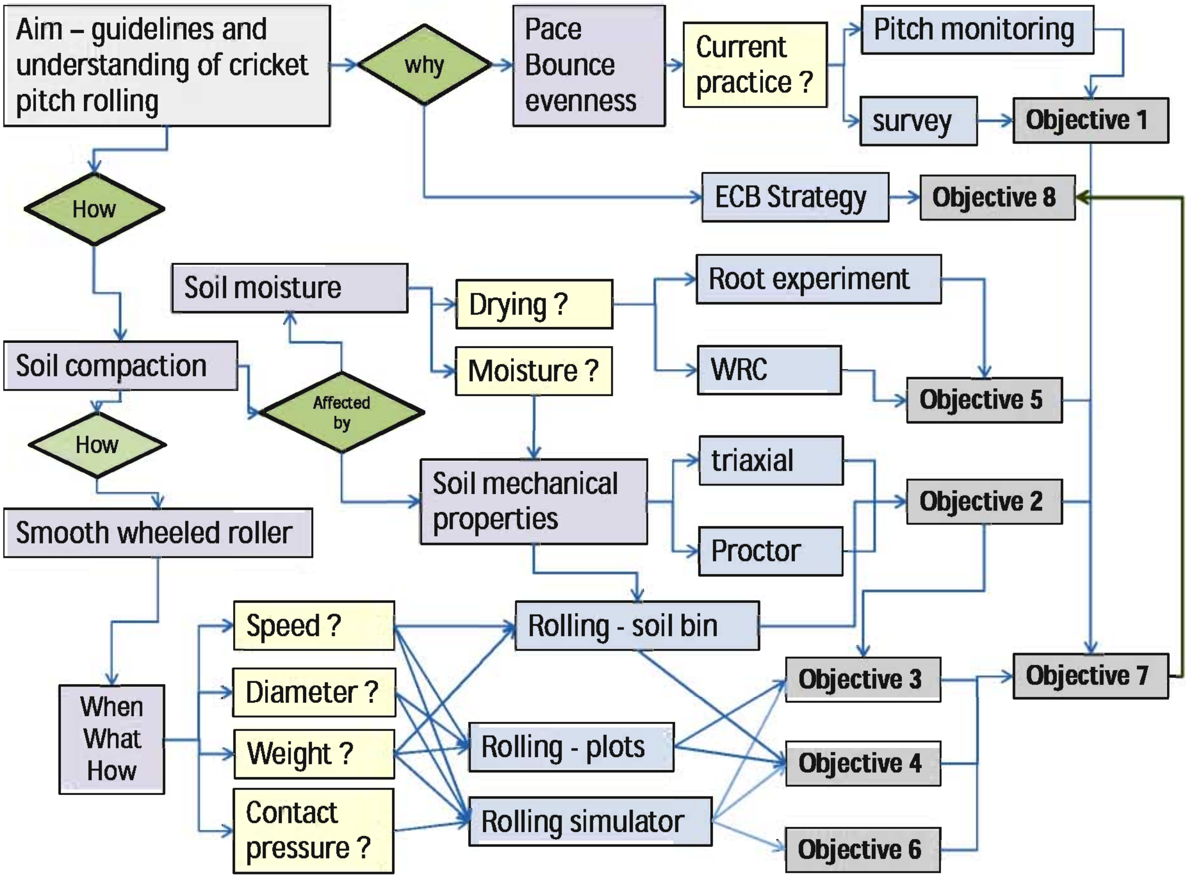


Figure 2.1 Project approach. ☐ = parameters and factors. ☐= properties to assess. ☐ = experimental work leading to the objectives. Objectives 1-6 inform Objective 7 (guidelines), which in turn inform Objective 8 (management benefits).

An evolution of the project experimental work occurred based on experimental findings. This resulted in some cross-experiment non-uniformity in experimental soil parameters, in particular soil moisture content. However this was necessary in order to determine the roller's maximum dry bulk density achievable (compactive potential) in specific soil physical conditions and the optimum soil moisture required to achieve it.

Chapter 3. Assessment of current rolling practice

3.1 Introduction

The extent of any variation in cricket pitch rolling management in the UK both in the spring and for summer pitch preparation is unknown. Without clear guidelines it is likely that individual groundsmen will create their own management rules and techniques based on their own circumstances and knowledge. A survey was undertaken to assess current management not only to determine the degree to which procedures differ but to also inform experimental design. The intention of the survey was to determine the extent of the variation in rolling regimes in the spring and for match preparation, and also to determine any differences in rolling management between different levels of cricket. Additionally the survey was designed to gather information on other aspects that affect rolling parameters including soil type, water application and autumn renovation.

Six pitches were also monitored at three locations for a year to gain an understanding of the fluctuations in soil dry bulk density that occur in a cricket pitch.

3.2 Survey methodology

A survey questionnaire was designed to give the respondent the opportunity to express their opinions as well as providing basic data on the facility that they managed and the rolling management that they adopt (Appendix 2). A mixture of dichotomous (yes/no), multiple choice and open-ended questions were used to encourage groundsmen to provide a picture of their rolling management. Open ended questions provide limited opportunity for statistical analysis however there was a possibility that comments could inform future work.

A draft copy of the questionnaire was previewed by the ECB's national pitch adviser as well as three first class county groundsmen to assess the suitability and ease of completion before being distributed. 450 copies were then sent to the 45 County Groundsman Associations (CGA) for distribution to their members with additional questionnaires being distributed at a number of groundsmen's functions. Letters were also sent to the 51 county pitch advisors asking them to encourage members to participate in the survey. First class groundsmen received questionnaires individually via a direct mailing from the ECB as part of their annual groundsmen's conference.

The questionnaire was also made available online through QuestionPro (2008) via a link from the Centre for Sports Surface Technology (CSST), Cranfield web page. Links to the CSST page were made available from the ECB, Play-Cricket, IOG and Pitchcare websites. Articles were produced on these websites advertising the questionnaire.

The survey was conducted between January and May 2006 and a prize draw was offered as an incentive to complete the questionnaires. The total production and distribution costs, including the online questionnaire and the prize draw (£100), were approximately £500. SPSS software (SPSS, Chicago, Illinois, USA) was used to analyse the results and comparisons between facility type and regions were derived. Non-parametric chi-square statistical analysis was performed where appropriate.

3.3 Pitch monitoring methodology

Monitoring of six pitches at three venues for changes in bulk density was undertaken between 9/03/05 and 23/02/06 to determine trends during a 12 month period. The three venues were representative of different levels of cricket facility, first class (Leicester CCC), premier club (Shenley Cricket Club) and lower league cricket (Cranfield University). Two soil cores were extracted from each pitch on each of four visits and the samples analysed for dry bulk density and moisture content (as detailed in Section 3.5). The number of samples taken was due to a restriction imposed by the venue managers and therefore this prevented meaningful statistical analysis.

3.4 Results of current practice assessment

3.4.1 Survey returns

More than 500 questionnaires were distributed to groundsmen around the UK, 71 were returned of which 64 were useable. 66 useable questionnaires were completed online providing a total of 130 questionnaires for analysis (Figure 3.1) (Appendix 2).

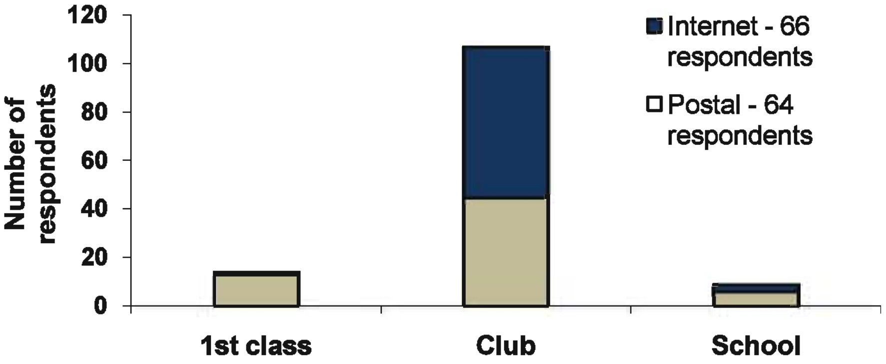


Figure 3.1 Questionnaire respondents by facility.

A sample size of more than 30 (population dependent) is considered to be required to be representative of a population (Salkind, 2004), and therefore this response was considered to provide valuable data for analysis. The response from the different facility type was in line with an expected distribution from the spread of the population. First class facility response was 78% from the 18 facilities in this sector, although not all questions were completed by all respondents. The school group includes municipal facilities as these were described as joint facilities in all but one questionnaire however with a sample size of nine they may not represent an accurate representation of the total population of school cricket facilities. School respondents were from independent schools with just one exception which could influence the funding available for cricket pitch management.

Analysis by region indicated significant* differences in respondent numbers between North East, E. Midlands and the South East regions (Figure 3.2 and Appendix 3).

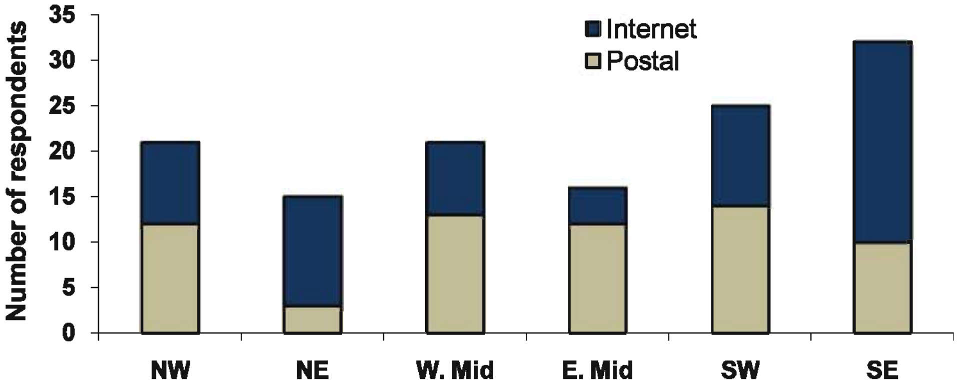


Figure 3.2 Questionnaire respondents by region NW = North West, NE = North East, W. Mid = West Midlands, E. Mid = East Midlands, SW = South West and SE = South East.

Reasons for this could include national distribution of facilities and distribution of questionnaires by CGA's rather than being indicative of groundsman apathy.

3.4.2 Question 1 - Facility size

Significant* differences between the number of pitches per square between First class and club were to be expected (Figure 3.3).

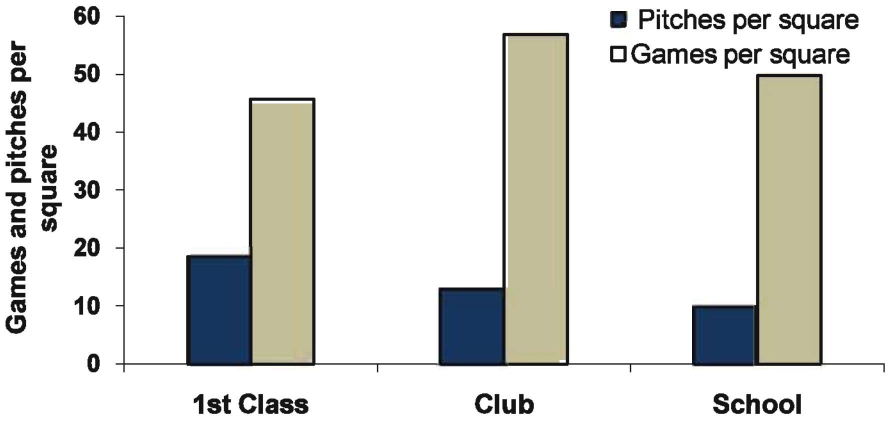


Figure 3.3 Games and pitches per square by facility.

First class facilities have larger squares to accommodate the higher standard of match pitch required. Pitches will not be reused for another game as frequently and certain pitches will be set aside for specific matches, such as test match pitches at certain grounds. Although the games per pitch ratio is greater for clubs and schools, meaning that pitches are reused more frequently, the length of the game in first class cricket is generally longer (see Section 1.2) and pitches will suffer greater wear per game.

3.4.3 Question 2 – Pitch construction and topdressing

Comparison of construction compared to topdressing soil indicated that first class pitches have moved in favour of the Ongar plus soil with 78.7% of respondents using this soil (Table 3.1). Club soil type indicates a far wider range of soil use with no distinct trend in use change. 49.9% of clubs use soils with < 30% clay however less appear to use the lowest clay soil that was used for pitch construction soil with an increase in use of the Ongar soil compared to construction being apparent. The use of Kaloam / Banbury soil by the clubs is an anomaly to the view that clubs favour lower clay pitches. 50% of the users of this soil were clustered in the South West indicating a possible local bias.

Table 3.1 Pitch construction soil and topdressing loam, percentage of respondents. Soil type ranked according to clay % content. Particle size distribution data courtesy of the ECB (2004). C = construction soil T = Topdressing soil.

Soil trade name	Clay %	silt %	sand %	First C	 T	Club C	 T	School C	 T
Mendip	25	59	16	-	-	20.5	10.2	20	20
Boughton Club	26	27	47	-	-	5.1	11.2	-	-
Boughton Kettering	26	29	45	-	-	7.7	7.1	-	-
Surrey 75	27	20	53	-	-	25.6	21.4	60	40
Ongar	30	40	30	58.4	78.7	10.3	17.4	-	-
Boughton County	31	30	39	8.3	7.1	-	-	-	-
Surrey 125	32	25	43	25	7.1	7.7	3.1	-	-
GOSTD Surrey S	34	25	41	-	7.1	-	-	-	20
GSB County	36	30	34	8.3	-	2.6	2	-	-
Kaloam / Banbury	37	47	16	-	-	20.5	27.6	20	20

The data determined that 14% of first class, 64% of club and 44% of school respondents did not answer the question on construction soil but only 9% of club and 33% of school respondents did not answer the question of topdressing soil used (Table 3.2).

Table 3.2 Matching of topdressing soil compared to construction soil as a percentage of respondents by facility type.

	First class	Club	School
Use same topdressing as construction soil	71	29	56
Use different topdressing soil to construction soil	15	7	0
Do not know (did not answer) construction soil	14	64	44
Do not know (did not answer) topdressing or construction soil	0	9	33

For respondents that answered both construction and topdressing questions there was a clear indication that first class groundsmen were more aware of the soil type used for construction and topdressing than the club groundsmen. However 15% of first class and 7% of club respondents were knowingly using different topdressing soil to the pitch construction soil (Table 3.2); although it is possible that these figures are a great deal higher if groundsmen are not aware of the construction soil type.

3.4.4 Question 3 - Rolling start date

Rolling start date in the spring was significantly* different between first class facilities and clubs and between schools (Figure 3.4). The first class playing season tends to start earlier than club fixtures and this is likely to be the main reason for the tendency to start earlier. Only one respondent said that they did no spring rolling.

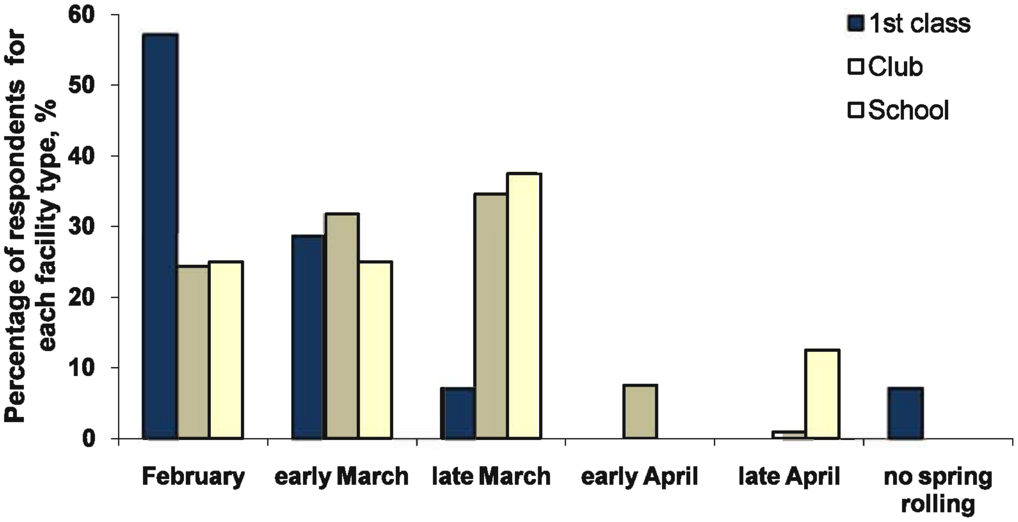


Figure 3.4 Spring rolling start date by facility type. First class facilities start earlier in the spring than other facility types.

Analysed regionally there is a tendency for the N West, N East and E Midlands to start later in the spring than the W Midlands, S West and S East and this is assumed to be at least in part for climatic reasons (Figure 3.5) with milder south and west climates encouraging earlier grass growth and therefore earlier drying of surfaces.

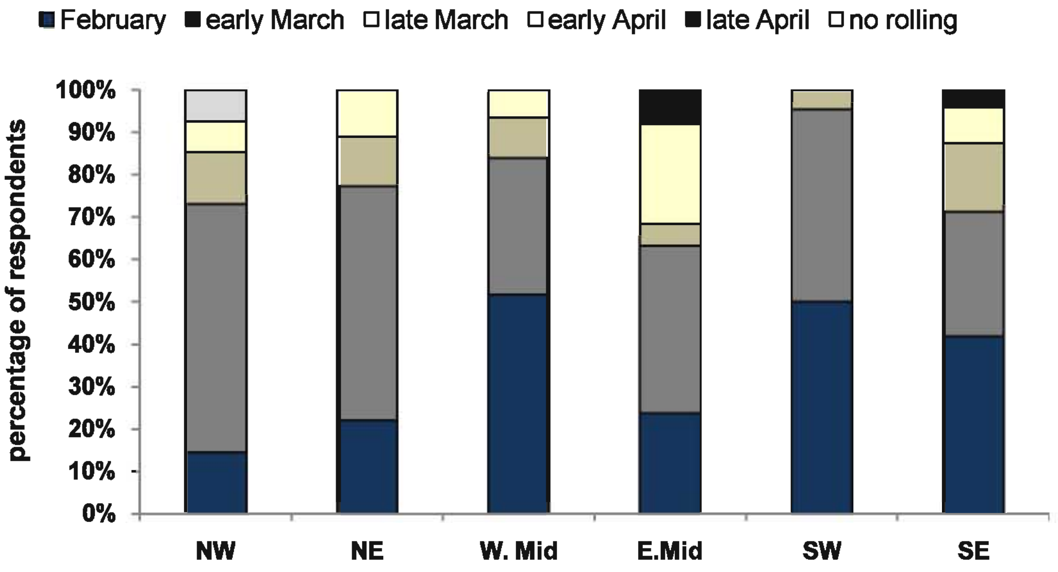


Figure 3.5 Spring rolling start date by region. NW = North West, NE = North East, W. Mid = West Midlands, E. Mid = East Midlands, SW = South West and SE = South East.

3.4.5 Question 4 – Start of rolling determinant

Many respondents took the opportunity to explain various techniques that they adopt for determining start date but a clear majority used some form of assessment of moisture content to decide when to start rolling in the spring (Figure 3.6).

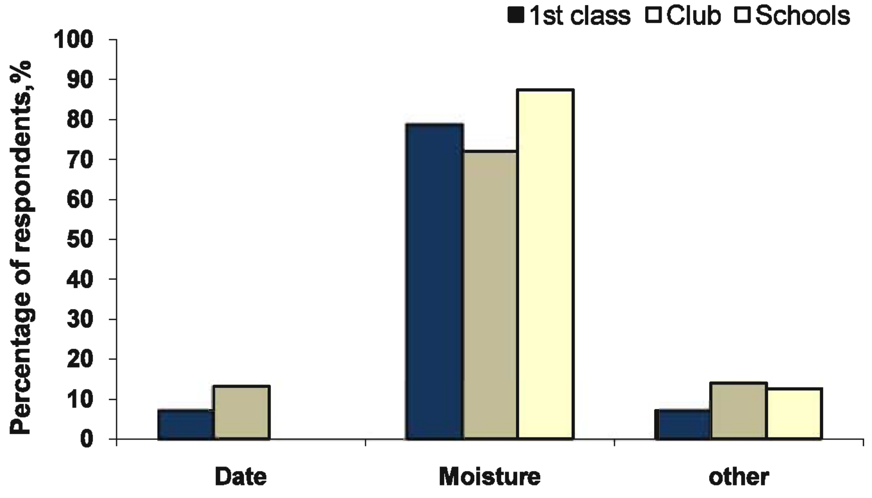


Figure 3.6 Determinant of rolling start date in the spring by facility type.

Although the moisture content was the main determinant of start date no respondent suggested that they used an actual measure of moisture content.

3.4.6 Question 5 – Rolling direction

Rolling only in the pitch direction would see a gradual permanent change in gradient along the pitch with a low point mid way along the length unless rolling can always be executed beyond the end of the playing surface. The spring is generally regarded as an opportunity to vary the direction of rolling to maintain a level square. The results of the rolling direction question indicate that the majority of groundsmen adopt this practice (Table 3.3) with only 4% of respondents rolling in the pitch direction only in the spring. Rolling in all directions in the spring is recommended by the ECB (2007) and current practice could be, at least in part, a result of training and education.

Table 3.3 Spring rolling direction, percentage of all respondents.

Rolling direction	Respondents, %
Pitch direction	65
Diagonally	83
Horizontally	90
No rolling	1

3.4.7 Question 6 – Pitch aeration

Autumn aeration with the intention of reducing compaction has become standard practice in recent years and only seven respondents indicated that they undertook no aeration at all. No aeration represented 21% of first class but only 4% of club respondents (Figure 3.7). Data on type of aeration equipment used as indicated by the survey can be seen in Appendix 4.

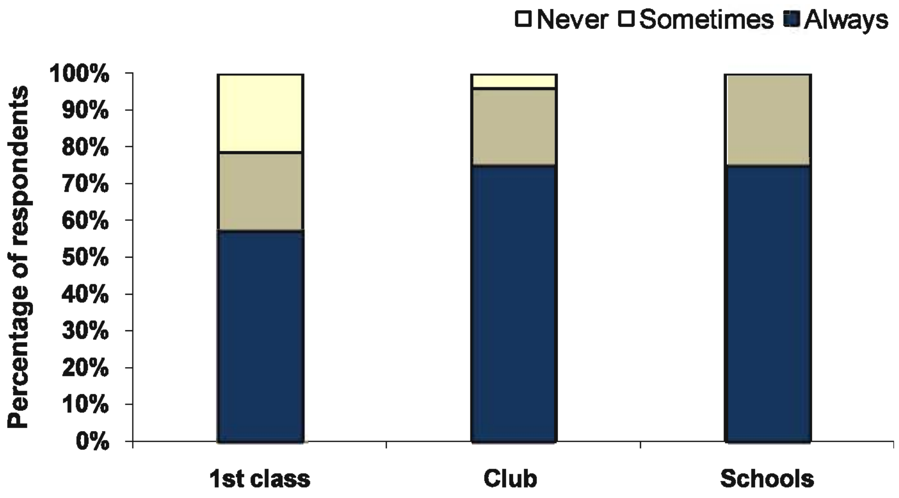


Figure 3.7 Autumn aeration for decompaction.

3.4.8 Question 7 – Autumn scarification

Autumn pitch renovation is relevant to the rolling project because the process of deep scarification is used as a form of aeration of the top 50 mm of pitch profile. Some form of scarification was carried out by all but two of the respondents (Figure 3.8).

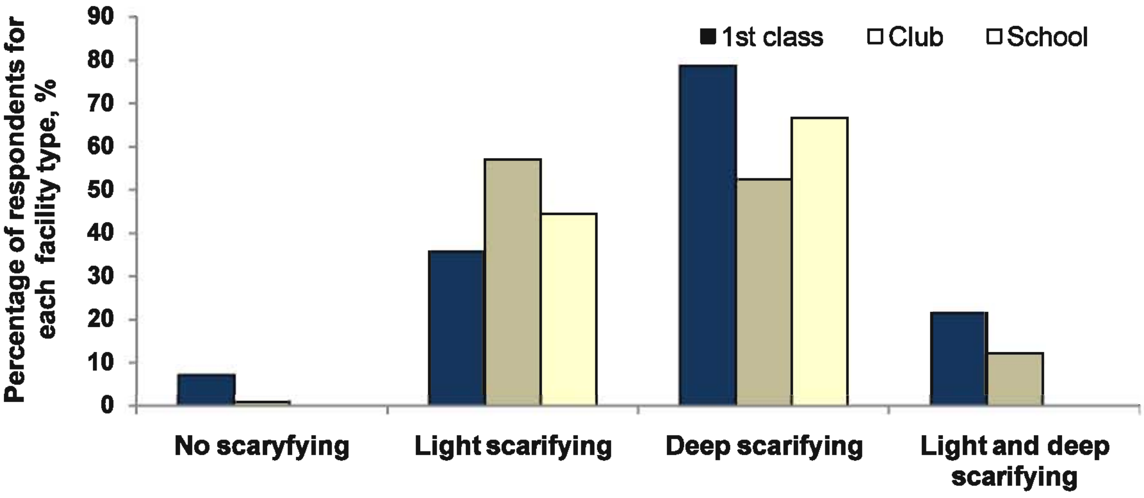


Figure 3.8 Autumn scarification by facility.

Often the choice between light and deep scarification varies from year to year with access to equipment or financial limitations influencing choice and decisions.

3.4.9 Question 8 – Roller specifications

Roller use in the spring was categorised into three periods, early, mid and late spring. The results are summarised in Table 3.4. A clear pattern of increasing roller weight and size occurs as the spring progresses however the range within the sample is high.

Table 3.4 Mean roller specifications for early middle and late spring rolling by facility. Range in dimensions is indicated in bracketed figures.

Spring rolling	Early	Middle	Late
Roller mass (kg)			
First class	315 (200-400)	1650 (1000-2500)	1970 (1700-3000)
Club	600 (30-3500)	1380 (60-3500)	1700 (500-3500)
School	230 (200-300)	1190 (265-1700)	1700 (1300-2200)
Diameter (mm)			
First class	200 (120-300)	640 (600-900)	670 (600-1000)
Club	460 (100-1500)	620 (150-1500)	720 (300-1500)
School	360 (250-600)	460 (250-600)	640 (600-900)
Width (mm)			
First class	830 (600-900)	1100 (900-1200)	1275 (1000-2000)
Club	900 (250-2000)	1000 (600-2000)	1100 (600-2000)
School	900 (900-900)	1230 (900-2000)	1200 (1200-1200)
Mass per meter (kg m^{-1})			
First class	380	750	773
Club	333	690	708
School	255	484	708

Conversely a decline in roller weight occurs during summer pitch preparation and the range is again high, particularly on match days, indicating very different pitch preparation strategies (Table 3.5).

Table 3.5 Mean roller weight for summer pitch preparation by facility type. Start roller weight is the weight of the roller on the first day of pitch preparation. Range of roller weights is indicated in brackets.

	Roller mass (kg)			
Facility	Start of preparation		Match day	
	kg	kg m^{-1}	kg	kg m^{-1}
1st class	2300 (1700-2500)	920 (680-1000)	1700 (100-3000)	680 (125-1200)
Club	1650 (500-2500)	750 (500-1000)	1450 (60-3500)	660 (100-1250)
School	1600 (1300-2000)	740 (550-920)	1750 (1300-2000)	800 (550-920)

The distribution of the sample is not always reflected in the mean. For roller weight in the spring the distribution is positively skewed for early and mid spring indicating that the mean is higher than the mode and median.

Roller drum number per machine data indicated 47.7% of groundsmen used a single drum machine to roll in early spring (which will include mowers used for rolling) reducing to only 3.1% in late spring where 66.9% used a 2 drum roller and 16.9% used a 3 drum roller. The remaining 13.1% did not roll in late spring. Data on roller drums is in Appendix 4 as well as data on roller manufacturer.

3.4.10 Question 9 – Rolling time, speed and passes

Table 3.6 summarises the mean spring rolling management in terms of the total time allocated to rolling the whole square, time spent rolling each pitch (total time per square/number of pitches) and speed. Similarly to roller specifications above the range is high indicating the diverse management practices carried out by groundsmen.

Table 3.6 Spring rolling. Time, roller passes and speed by facility. Range in brackets.

	Time per square hours	Time per pitch hours	Passes per pitch no.	Rolling speed km h^{-1}
First class	43	2.5	69	0.69
	(10-110)	(0.5-5.5)	(5-280)	(0.25-1.27)
Club	30	2.3	51	0.65
	(2-96)	(0.1-7.2)	(3-325)	(0.1-3.4)
School	19	1.9	46	0.61
	(9-35)	(0.7-5)	(8-150)	(0.3-0.75)
Survey mean	31	2.3	53	0.67

The range within clubs and first class is positively skewed with the majority of respondents rolling at less than 1 km h^{-1} and 0.8 km h^{-1} respectively.

Summer rolling results again indicated large ranges in management Table 3.7.

Table 3.7 Summer pre-match rolling. Time, roller passes and speed by facility. Range in brackets.

	Time per pitch hours	Passes per pitch no.	Speed km h^{-1}
First class	6.4	127	0.57
	(3.3-14.6)	(35-236)	(0.24-1.52)
Club	3.3	77	0.68
	(0.2-15)	(5-540)	(0.1-3.0)
School	7	70	0.4
	(0.5-19)	(6-386)	(0.3-0.5)
Survey mean	3.8	83	0.65

Pre-match rolling data indicates a spread over a varying time span prior to a match from 2-3 weeks to just one day before. First class respondents showed a tendency to reduce rolling over the week prior to a match from peak rolling frequency eight days before a game. Clubs indicated a more consistent number of roller passes during the week before a match however many groundsmen stated that they would roll more if they had more time (Figure 3.9).

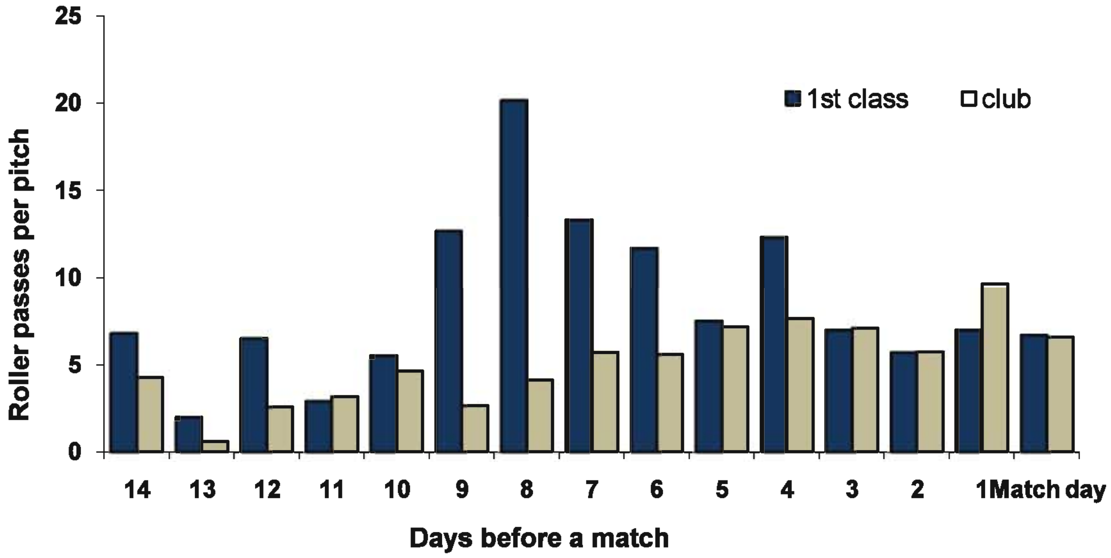


Figure 3.9 Amount of roller passes on a pitch during the 14 days before a match is played.

3.4.11 Question 10 – Watering of pitches before matches

To ascertain when water application occurs as part of the overall pitch preparation process respondents detailed when they would apply water under dry or pitch covered conditions. There were clear indications from data and questionnaire comments that first class facilities work on pitches 14 days or more before a match whereas clubs had a tendency to work on a 6/7 day cycle i.e. preparation starting on the Monday for a match the following weekend (Figure3.10).

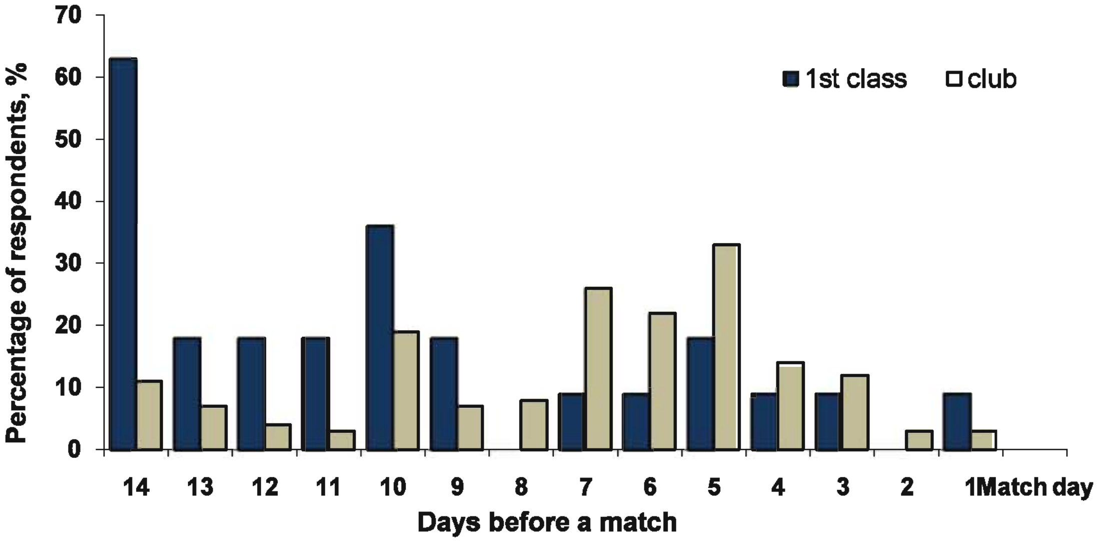


Figure 3.10 Days that water is applied to a pitch during the 14 days before a match.

3.4.12 Question 11 – Players comments and the amount of rolling

Having prepared the pitch the groundsman usually assesses its playability from team performance, umpires assessments or players comments. 41% of all respondents indicated that they had noticed a link between the amount of rolling undertaken and player's comments and 49% indicated that they had not. 10% declined the opportunity to comment.

3.4.13 Pitch monitoring

Six pitches at three locations were measured for bulk density and moisture over a 12 month period (September 2005 to September 2006) to examine general trends in pitch characteristics. Mean results for all locations indicated an increase in dry bulk density to a depth of 60 mm over the summer period but a decline in dry bulk density between 60 mm and 120 mm (Table 3.8; full details in Appendix 5).

Table 3.8 Summary of initial pitch monitoring results over time and depth for dry bulk density and gravimetric moisture content θ_m.

	09/03/2005		01/07/2005		11/10/2005		22/02/2006	
	$\theta_{m.}$	Density	$\theta_{m.}$	Density	$\theta_{m.}$	Density	$\theta_{m.}$	Density
Sample depth	m/m	g cm^{-3}	m/m	g cm^{-3}	m/m	g cm^{-3}	m/m	g cm^{-3}
0 - 30 mm	35.09	1.23	21.69	1.41	28.17	1.46	42.40	1.28
30 - 60 mm	27.64	1.42	17.98	1.58	23.97	1.63	28.46	1.52
60 - 90 mm	20.84	1.82	17.61	1.72	22.23	1.64	24.43	1.53
90 -120 mm	20.17	1.78	20.23	1.68	21.44	1.68	24.72	1.54

The moisture contents were lower in midsummer (July, 2005) than in the spring (March, 2005) which could account for some of the increase in dry bulk density in the 0-60 mm depth. Higher dry bulk density in the autumn (October, 2005) despite an increase in moisture content compared to the summer may have been associated with rolling. A decline in dry bulk density for all depths over the winter 2005/2006 either as a result of swelling from an increased moisture, frost heave or autumn aeration.

Only a limited sample replication was possible due to facility manager's restrictions and therefore no statistical analysis has been undertaken.

3.5 Discussion and summary of current practice

The survey provided data on current rolling management in the UK for spring and summer pitch preparation. Patterns of rolling practice were evident although the range within most management procedures is high thus providing the project with the scope to improve overall efficiency. Pitch monitoring results gave an initial insight into seasonal trends but was not accompanied by any data on roller use because the groundsmen involved did not keep adequate records.

Differences in practice were apparent in most aspects of the rolling procedures both within and among types of facility. The wide range of management procedures highlighted a diversity of understanding and underlined the lack of guidance. Although it is likely that there is more than one way to produce a pitch of the required standard the wide diversity in practice represents an opportunity for many groundsmen to improve their pitch quality and/or efficiency by providing them with the knowledge to do so.

First class facilities have more pitches than the average club venue and will therefore require more labour input for maintenance particularly if spring rolling is undertaken, which was the case for all but one respondent. The total hours of cricket played at first class facilities is likely to be greater than for clubs although the drive from the ECB to increase participation particularly at grass roots level (ECB, 2005) may require increased use of existing facilities. A higher turnover of use may become necessary where expansion in other ways is not possible. Improved understanding of rolling for pitch preparation should be able to inform this requirement.

Matching soil types when topdressing has been advised since Stewart and Adams (1968) and in recent official publications (Adams *et al*, 2004). Survey returns indicate that 71% of first class respondents use the same soil for topdressing as the construction soil and only 29% of club respondents. However these figures are for those that knew the construction soil and in the case of club respondents the majority (64%) were unable to answer this question. Furthermore 9% of club respondents (0% first class) indicated no knowledge of the type of soil they were applying. This apparent lack of uptake of available advice is more prevalent within the club respondents.

Soils used throughout the project experiments (selected prior to the survey results, see Section 3.4.3) were OL (Ongar loam), as favoured by 78.7% of first class facilities and KL (Boughton Kettering) used by 7.1% of clubs. The KL soil is however similar in particle size distribution to a number of other soils which in total were used by 49.9% of club respondents.

Rolling in the spring was shown to be standard practice and that start date was likely to be strongly influenced by the start of fixtures. First class facilities will often feel they are unable to wait for ideal natural conditions and often use pitch covering in early spring to initiate a drying process. The majority of respondents (74%) indicated that moisture was the determinant of when they started rolling however no respondent indicated that they measured moisture content. Various methods were described but essentially they all involved a manual test for physical resistance resulting from foot or finger pressure or by insertion of an object into the profile. This fact needs to be considered when producing guidelines as this is effectively a measure of penetration resistance rather than moisture content.

Soil aeration at the end of the playing season was considered by most respondents to be necessary with only 5% indicating that they never undertook aeration. 50% of respondents also indicated some form of deep scarification during autumn renovation. Both of these activities have the potential to reduce bulk density and change soil structure. The main expressed justification for this is to improve grass establishment and root penetration leading to enhanced grass health and moisture removal potential in the following summer. Reduction in bulk density could increase drainage and combined with the reduced bulk density result in greater air voids in the spring leading to an earlier start after soils reach field capacity. High bulk density soils will remain close to saturation at field capacity and not facilitate rolling until evapotranspiration occurs although the need to do so is obviously less. It follows that by reducing bulk density in the autumn there is a greater requirement in the spring for rolling to restore the previous season’s pitch bulk density. Guidelines for spring rolling will need to consider the initial dry bulk density which will undoubtedly vary between venues.

Wide ranges determined between the respondents for roller specifications and operation indicates that a mean for a particular activity is not necessarily an indication of good or appropriate practice. Within the ranges there are clear indications of common practice and prudence would dictate the use of the modal average to provide the starting point for experimental design. Principles underlying rolling practice do emerge and match current recommendations (ECB, 2007) i.e. increasing roller weight as the spring progresses. Actual roller speed has never been defined but two separate methods to calculate speed, from the answers to a series of questions within the questionnaire, gave similar results indicating that speed figures produced by the survey can be viewed with a reasonable level of confidence.

Patterns of rolling and pre-match watering show variations between facilities and are likely to reflect a number of factors but the most consistent comment from club respondents was lack of time to carry out more pitch preparation. Guidelines will need to address the different labour availability if experimental findings indicate the need for greater time spent rolling.

When providing guidelines to practical people it is important to understand their limitations with regard to equipment, time and other resources. The survey produced valuable data on current practice which will enable the guidelines to be targeted to get maximum benefit to all facilities and therefore meeting the ECB requirements. In addition to the benefits to this project in terms of experimental design and preparation of guidelines the survey results also provide a historical record and a valuable benchmark for future surveys to assess the impact of any guideline recommendations.

Chapter 4. Soil physical and mechanical characterisation

4.1 Introduction

Soil physical properties vary between soil type with regard to the mineral and organic content. With at least 20 soils commercially available marketed specifically for cricket pitch use it is likely that this will be reflected in a variation between cricket facilities in terms of physical soil properties. Two cricket loams were selected for the project to reflect the range of clay contents in the available soils.

Soil mechanical properties are a result of the soil mineral content, soil moisture content, bulk density and organic matter as well as the earth pressure at rest confining pressure. The working hypothesis that soil mechanical properties change in relation to the soil moisture content thereby affecting the load required for compaction, is investigated in this chapter.

Cricket soils are subjected to repetitive loads to increase soil bulk density. Laboratory controlled dynamic testing of soil compaction under different moisture and density conditions were carried out to characterise the relationship between moisture, dry bulk density and soil compaction in terms of mechanical parameters, stiffness and elasticity.

4.2 Methods used to determine soil characteristics

A number of tests were undertaken to determine the physical properties of the soils used in the project experiments. To determine strength and failure mechanisms of these soils compaction, translational shear strength and triaxial compression tests, both static and dynamic, were completed. In addition an experiment was conducted in the soil bin at Silsoe to gain initial data on the relationship between rolling and dry bulk density.

4.2.1 Soil type, particle size distribution and physical parameters

Two soil types were used throughout the project and were selected on the advice of the project thesis committee with the intention of being representative of a relatively high clay cricket loam typically used at a first class facility and a low clay cricket loam more typical of club or school level cricket (Table 3.1). The high clay soil was sourced from C H Binder Ltd, Ongar, Essex and is marketed as Ongar Loam (OL). The low clay soil was purchased from Boughton Loam and Turf Management Ltd, Kettering, Northamptonshire and is marketed as Kettering Loam (KL). The particle size distribution for these soils as analysed using the pipette method (Cranfield University Soil Laboratory Standard Operating Procedure NR-SAS/SOP5/1 based on ISO 11277:1998) on their arrival by Cranfield University soil laboratory are presented in Table 4.1.

Table 4.1 Soil particle size distribution and textural class for the two project soils.

	Ongar	Kettering
Coarse sand (2 mm - 0.600 mm)	4.64	4.10
Sand (0.600 - 0.212 mm)	14.66	26.90
Fine sand (0.212 mm - 0.063 mm)	10.48	16.20
Total sand	29.78	47.20
Silt	39.84	27.30
Clay	30.38	25.50
Textural Class (UK texture classification):	Clay Loam	Clay Loam

Organic matter has been shown to influence playability factors and achievable soil dry bulk density (Adams *et al,* 2004) therefore it is necessary to measure the level within the soil being tested. Oxidisable organic matter was determined for the soils used in all of the experimental work. Soil samples were taken from the project experimental plots (see Chapter 5) and OM measured using the British Standard Methods of Test for Soil for Civil Engineering purposes Part 3. Chemical and Electro-chemical Tests BS1377: Part3: 1990.

Soil particle density was determined for the soil using the Pycnometer method (ASTM, 1958) to aid in the measurement of porosity. Soils were also tested for plastic limit by rolling of moulded wet soil into a 3 mm thread repeatedly until the thread dried enough to cause crumbling of the thread at 3 mm; the soil is then dried to measure moisture content.

The intention was to determine differences between these soils which were used in all project experiments.

4.2.2 Laboratory soil compaction tests

Two methods for soil compaction were used to determine optimum compaction moisture contents and dry bulk density, the British Standard Method BS1377: Part4: 1990 (adapted from the A.A.S.H.O. test designation T.99-38; B.S. 1377:1948, test no.9), known as a Proctor test (Proctor, 1933), and the modified AASHO compaction test. Both tests involve packing soil into a mould at different moisture contents to obtain a range of gravimetric moisture content and dry bulk density combinations. This data enables the determination of an optimum moisture content at which the maximum dry bulk density was achieved. The two methods involve a similar procedure but differ in the compactive effort used in the packing process and are described in more detail in Section 1.5.2.1. The different methods determine different optimum dry bulk density and moisture and can potentially be compared to different roller compactive potential.

For calculation of air voids at saturation i.e. zero air voids Equation 4.1was used (DSIR, 1951)

$$\text{Air voids at saturation} = \frac{\rho_s}{1+\theta_m\rho_s} \qquad [4.1]$$

and dry bulk density at a specific air voids percentage Equation 4.2

$$\rho_d = \frac{\rho_s\,(1\text{-}A_v)}{1+\theta_m\rho_s} \qquad [4.2]$$

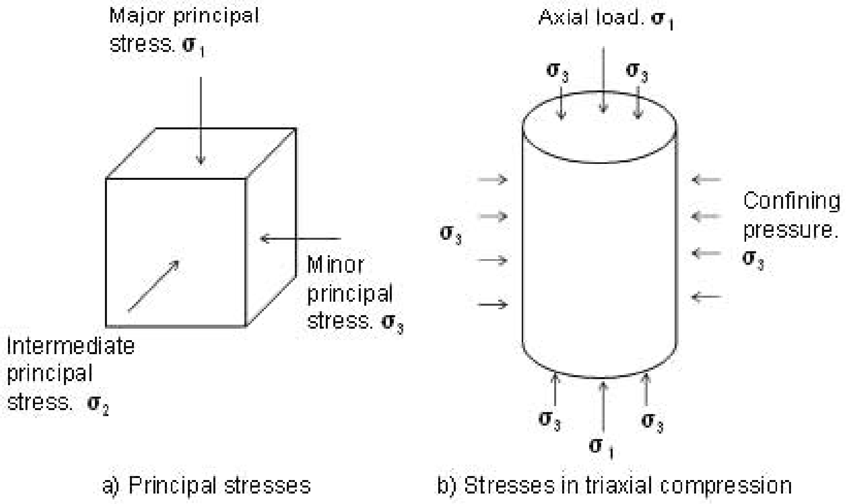
where ρ_s = particle density (g cm^{-3}), A_v = air voids (%) and θ_m = gravimetric moisture content (%).

4.2.3 Soil strength measurement

Compaction increases shear strength and this can be measured by the shear stress at failure. This was determined using two methods: the translational shear box and the quick, undrained triaxial compression test. For the translational shear box, OL soil was prepared at 6% and 18% moisture content. The 60 x 60 x 20 mm samples were then placed in the translational shear box and subjected to an incremental strain at a rate of

1.25 mm min^{-1}. The shear stress at failure was determined for normal stresses of 15.6, 29.3, 42.9, 56.5 and 70.1 kN m^{-2}.

For the quick, undrained triaxial compression test soil is subjected to compressive forces acting in three orthogonally opposed directions (σ_1, σ_2 and σ_3) (Figure 4.1a).



a) Principal stresses b) Stresses in triaxial compression

Figure 4.1 Principal stresses and their relevance to triaxial compression.

The three planes on which these stresses act are known as the principal planes and the stresses are the principal stresses. When a cylindrical soil specimen is subjected to triaxial compression it is loaded in two principal axes (Figure 4.1b). The intermediate stress σ_2 is equal to the minor principal stress σ_3 in symmetrical soil specimens therefore the stress can be measured in two dimensions only. The cell pressure (confining pressure) applied by the triaxial apparatus is σ_3 and acts equally in all directions and therefore does not induce any shear stress. The axial load is applied (denoted by σ_1) causing stress in the axial direction only. Total axial stress is therefore $\sigma_1 - \sigma_3 = q$, the deviator stress and is plotted against strain to give strength at failure i.e. maximum deviator stress (Equation 4.3).

$$q = \sigma_1 - \sigma_3 \qquad [4.3]$$

Using triaxial apparatus (ELE International Ltd Leighton Buzzard, UK) 38 mm diameter x 72 mm length cylindrical samples were failed in shear at total confining stresses of 35, 69, 103 and 138 kN m^{-2}, at a strain rate of 1.5 mm min^{-1}. Samples were prepared at 15, 18 and 23% gravimetric moisture content and tests were conducted in triplicate (these did not exactly match the moisture contents used in the translational shear experiments due to the method of soil wetting used by laboratory technical staff in this experiment and time did not allow for further experimentation). In both methods, dry bulk density was constant at 1.50 g cm^{-3}. Linear models of soil failure at a shear stress (τ, kN m^{-2}), as a function of normal stress (σ, kN m^{-2}) were determined by the Mohr-Coulomb theory of soil failure (Lambe & Whitman, 1969) (Equation 4.4; see also Section 1.5.2.3).

$$\tau = c + \sigma' \tan \phi \qquad \textbf{[4.4]}$$

The models were determined by linear regression in the translational shear box test and by the construction of Mohr's circles for the triaxial test. Mean values of cohesion (c', kN m^{-2}) and internal angle of friction (ϕ', degrees, °) were analysed by ANOVA.

4.2.4 Dynamic compaction using triaxial equipment

Compaction of soil results in an increase in dry bulk density and a reduction of air void volume. The roller provides a compactive force governed by roller load, soil contact area and forward speed. The duration of loading is relatively short in cricket pitch rolling i.e. with a forward speed 0.3 km h^{-1} and a contact arc of 0.05 m, contact time is 0.5 s. To determine the force required to compact soil with particular physical properties a GDS Dynamic testing system (Minidyn 2Hz DYNTTS) was used (GDS, 2008). The apparatus consists of a pressure cell where samples are placed before filling with water to pressurise up to pressures in excess of 700 kPa (Figure 4.2). An axial actuator provides a dynamic load to the sample for a user programmable duration for a minimum of 0.5 s (2Hz).

Samples are only partially constrained from radial expansion within the pressure cell as load is applied. Hall Effect local strain transducers were used to obtain greater accuracy in the measurement of volume change by measuring radial and lateral changes in the sample resulting from a dynamic load (Figure 4.2).

Figure 4.2 GDS Minidyn 2Hz DYNTTS equipment (left) Prepared sample for dynamic testing with Hall Effect local strain transducers measuring radial and lateral movement.

To simulate soil radial stress conditions in the triaxial apparatus σ_3 must be equivalent to an elastic equilibrium (when a small change in stress produces a corresponding and reversible change in strain (Whitlow 2004)) of the sample and this is a function of soil properties apparent cohesion (c), angle of internal friction (ϕ) and pore pressure.

The principle of earth pressure at rest (σ'_h) describes a state of elastic equilibrium when no strain is being applied to the soil in any direction (Equation 4.5):

$$\sigma'_h = K_o \sigma'_v \qquad [4.5]$$

$$K_o = [1 - \sin \phi' \text{ (internal angle of friction)}] \qquad [4.6]$$

Where K_o = Coefficient of earth pressure at rest (proposed by Jaky (1944)) and σ'_v = vertical effective stress (kPa).

However using σ'_h as a measure of σ_3 gives a figure that is not representative of a surrounding soil mass. Including pore pressure and apparent cohesion into the calculation provides a more realistic measure of the soil state.

Pore pressure at saturation is assumed to be zero. As a soil dries pore pressure increases resulting in a change in the soil strength properties. To estimate pore pressure and to apply this to a change in strength within a given sample, suction strength (τ_u) and cohesion at saturation (c'_s) were included into an expression that represented earth pressure at rest suitable for application as radial stress (σ_3) in triaxial (Equation 4.7):

$$\sigma'_{ht} = \sigma_3 = \sigma_v - \tau_u (1 - \sin\phi) + c'_s \qquad \textbf{[4.7]}$$

To calculate the required σ_3, ϕ and c_s were derived from the Mohr-Coulomb equation resulting from triaxial quick undrained compression results as detailed in Section 4.3.3. σ_v (vertical stress) was calculated for a 100 mm depth of overburden soil. Suction strength (τ_u) has been calculated from soil water release characteristic data (see Section 4.3.5). Matric suction was adjusted to give τ_u by applying the model proposed for this purpose by Vanapalli *et al* (1996) (Equation 4.8):

$$\tau_u = (u_a - u_w) \tan\phi\ (\theta - \theta_r / \theta_s - \theta_r) \qquad \textbf{[4.8]}$$

where (u_a - u_w) is the matric suction (u_a air entry suction, u_w actual matric suction) , ø is the internal angle of friction, θ is the volumetric water content, θ_s is the saturated volumetric water content and θ_r is the volumetric water content at residual conditions.

A second, logarithmic model proposed by Tekinsoy *et al* (2004) (Equation 4.9) was used to check the accuracy of the measure for τ_u (due to potential inaccuracies in soil water release characteristic curves) and provided similar results.

$$\tau_u = \tan\phi\ (u_a + P_{at}) \ln (u_w + P_{at} / P_{at}) \qquad \textbf{[4.9]}$$

Where P_{at} = atmospheric pressure

Utilising Equation 4.7, σ_3 was derived for various levels of dry bulk density between 1.20 g cm^{-3} and 1.80 g cm^{-3} at 15%, 20% and 25% gravimetric moisture content.

Figure 4.3 show the result of this analysis and are the cell pressures used in the dynamic compaction experiments.

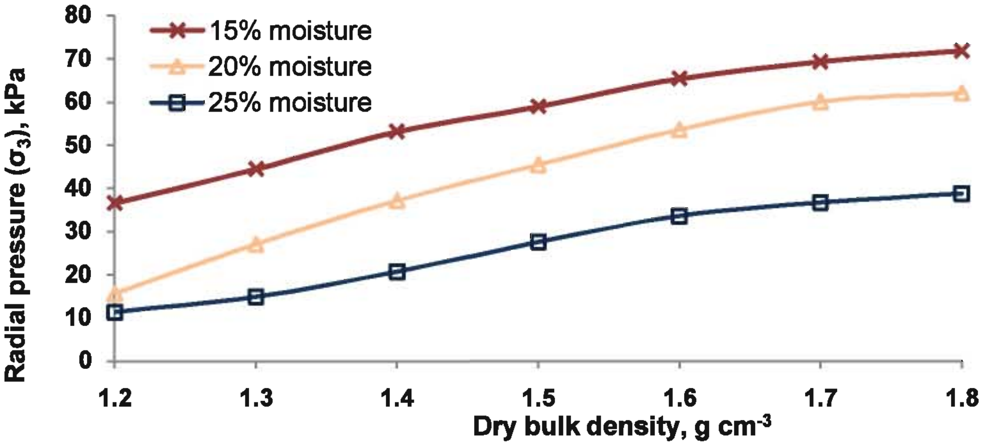


Figure 4.3 Radial pressure for dynamic triaxial experiments derived from Equation 4.7 ($\sigma_3 = \sigma_v - \tau_u (1 - \sin \phi) + c'_s$).

Prior to experimentation tests were run to verify the appropriateness of these figures. The calculated σ_3 was applied to prepared samples of a known dry bulk density and moisture content in increments of 20, 40, 60 and 80 kPa and then returned to zero stress to ensure a fully recoverable elastic reduction in volume. An example of the results of this process is shown in Figure 4.4.

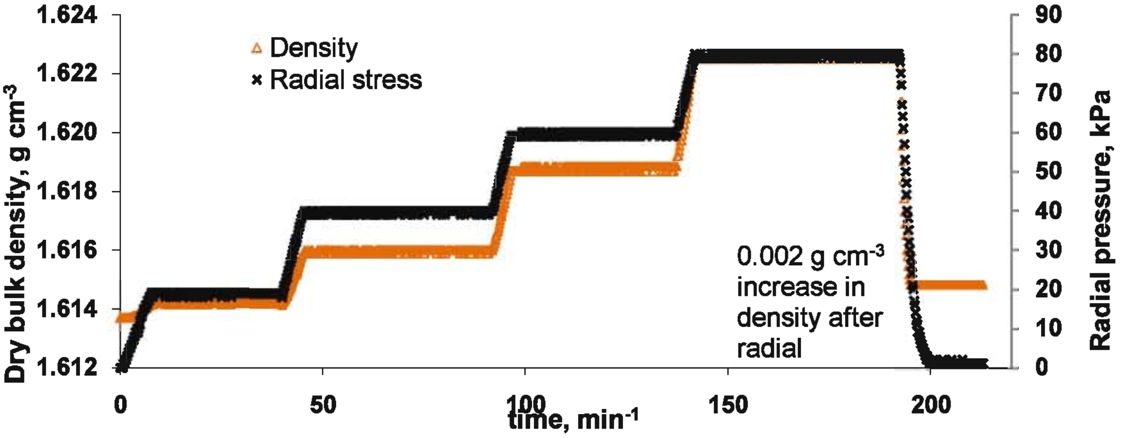


Figure 4.4 Radial pressure applied to an OL triaxial sample and the change in dry bulk density resulting from changes in the sample volume. Gradual increases in radial pressure, with time to allow for pressure equilibration in the sample, to a maximum pressure as calculated by Equation 4.7. Final pressure reduction to zero resulted in an increase in dry bulk density of 0.002 g cm^{-3} due to a reduction in sample volume.

This process was repeated for a number of density and moisture combinations which all showed an increase in dry bulk density of less than 0.005 g cm^{-3} of starting density.

Samples 70 mm x 140 mm were prepared for four dry bulk densities, 1.20, 1.40, 1.60 and 1.80 g cm^{-3} and at three gravimetric moisture contents, 15%, 20% and 25%, totalling 12 treatments. After being placed in a rubber sleeve and positioned in the triaxial pressure cell they were subjected to the predetermined σ_3 before a dynamic axial stress was applied for 0.5 s, being equivalent to a rolling speed of 0.3 km h^{-1}. Relationships between stress, plastic strain (permanent strain) and recoverable elastic strain were determined in relation to maximum strain (Figure 4.5).

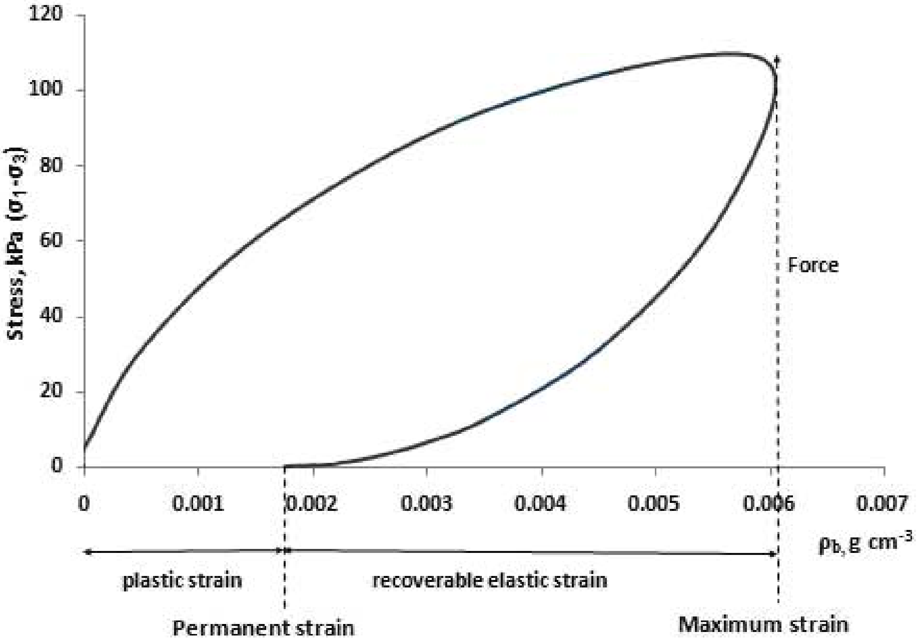


Figure 4.5 Example of strain, measured by change in dry bulk density, versus stress relationship for one dynamic axial load. Maximum strain is recoverable by elastic strain leaving a permanent increase in density being the element of plastic strain.

Strain was measured in terms of changes in dry bulk density assessed by axial strain change as well as movement in radial strain measured by the Hall Effect transducers.

Soil stiffness under a dynamic load (k_d) was measured using Matlab scripts developed by Guisasola (2008) which defined a dynamic secant stiffness moduli as a ratio between maximum axial stress (σ_{max}) and maximum axial strain (ε_{max}) (Equation 4.10).

$$k_d = \frac{\sigma_{max}}{\varepsilon_{max}} \qquad [4.10]$$

Stress was increased until a residual increase in dry bulk density of 0.005 g cm^{-3} occurred resulting from an applied load. This figure was considered to be minimum economic efficiency for cricket pitch rolling and equates to 20 roller passes on a cricket pitch to increase dry bulk density by 0.1 g cm^{-3}. The maximum stress required to increase the sample density by the acceptable minimum was determined for each sample.

4.2.5 Soil bin rolling experiment

A rolling experiment was conducted in the soil bin at Silsoe to establish an effective experimental procedure for the field studies and to gain initial data on the relationship between rolling and dry bulk density and the compaction potential of two roller weights.

Experiment objectives

1. To determine the compaction potential (i.e. maximum dry bulk density) of roller weights 403 kg m^{-1} and 603 kg m^{-1} under optimum soil physical conditions.
2. To determine the number of passes required to achieve a maximum dry bulk density with two different roller weights.
3. To determine the number of passes required to achieve a maximum bulk density with rollers towed at two different speeds.
4. To determine change in contact footprint resulting from rolling for the two roller weights tested.
5. To determine lateral force requirements for roller treatments

Soil bin rolling methodology

Two separate profiles of OL soil measuring 8 m x 1.6 m x 0.2 m were constructed. Four 50 mm layers of OL were separately compacted with one pass of the processing unit's 700 kg roller. A measured quantity of water was added to each 50 mm layer and left for 24 hours to achieve a relatively uniform gravimetric moisture content of 20% through the profile and across the soil bin (20% moisture content was selected on the recommendation of cricket industry consultants as to be the normally recommended moisture content for rolling; this experiment was conducted before a Proctor optimum moisture test was undertaken.

The experimental roller[1] used measured 1200 mm (width) x 600 mm (diameter) and was operated at two weights and two speeds giving four roller treatments (Table 4.2).

Table 4.2 Four roller treatments used in soil bin rolling experiment.

Roller	Mass, kN	Mass, kg m^{-1}	Diameter, mm	Speed, km h^{-1}
1	4.7	403	600	2
2	4.7	403	600	1
3	7.5	638	600	2
4	7.5	638	600	1

The roller was attached to an extended octagonal ring transducer (EORT) (Godwin, 1975) to measure lateral draft force and was towed by the soil bin processing unit (Figure 4.6).

Figure 4.6 Roller mounted on a strain gauge (left) to measure force and being towed in the soil bin at Cranfield University, Silsoe by the soil bin processor (right).

The first prepared profile was split along the length of the bin into two 4 m sections and rolled with a 4.7 kN (403 kg m^{-1}) (un-ballasted) roller. The first 4 m section was rolled at 1 km h^{-1} and the second section was rolled at 2 km h^{-1}. For the second profile, the roller was increased to 7.5 kN (638 kg m^{-1}) and operated at the same speeds as in the

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[1] The roller was supplied and adapted for use with the processing unit by Autoguide Equipment Ltd, Calne, Wiltshire. UK

first profile. For each specification, the roller was towed by the soil processing unit in one direction only for repeated passes along the profile.

Measurements of the soil profile were made at a test location point that was allocated using a randomised grid after 0, 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 40, 50, 60 and 70 roller passes:

- 42mm diameter cylindrical cores were divided into three samples depths: 0-50 mm, 50-100 mm and 100-150 mm. Samples were oven dried to measure dry bulk density and moisture content (θ_m and θ_v).
- Shear vane (vane dimensions 19 mm diameter x 29 mm depth) measurements for three depths (50 mm, 100 mm and 150 mm). The shear vane measurement expresses the shear involved in the detachment of soil particles by flow (Zimbone *et al*, 1996).
- Roller contact pressure was calculated from static contact footprint width.
- Draught force was measured during roller passes by the EORT attached to the roller drawbar and logged at 20 Hz.

Samples were also taken to measure soil water release characteristics of the compacted soil at intervals of 0, 4, 10 and 70 roller passes following the method Cranfield University method NR-SAS/SOP 24/1.

The measurement results were subjected to a statistical analysis of variance to a significance level of $p < 0.05$.

4.3 Results of soil characterisation

Soil physical properties were determined for the OL and KL soil used in the project experimental work. These soils were then subjected to static and dynamic mechanical strength tests.

4.3.1 Soil physical properties

The soil types OL and KL as detailed in Section 4.2.1 were assessed for organic matter (OM) and particle density (ρ_s). OM was tested on the Experimental plots (Chapter 5) 12 months after construction at 5 different depths to 150 mm and the overall mean for both soils and all depths was determined to be 3.01%. No significant differences were determined between soil type, but differences were significant* for depth (Figure 4.7).

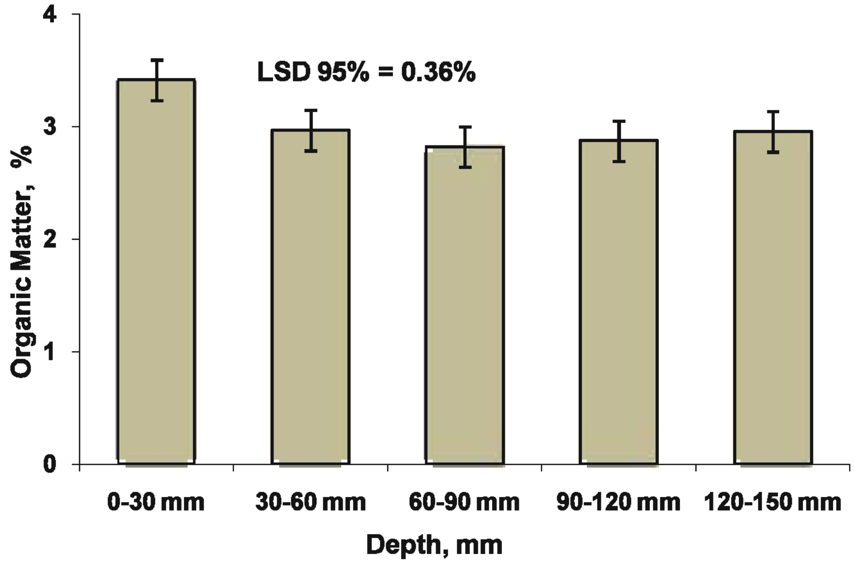

Figure 4.7 Organic matter in experimental trial plots at five depths (April 2006).

Depth 0-30 mm had significantly* greater OM (3.4%) compared to all of the other depths which were not significantly different from each other. Accumulation of rootmass in the 0-30 mm depth is likely to increase soil OM.

Particle density (ρ_s) and plastic limit were also determined (Table 4.3).

Table 4.3 Summary of soil physical properties: organic matter (OM), particle density (ρ_s) and the plastic limit.

Soil	Sand %	Silt %	Clay %	OM %	ρ_s g cm^{-3}	Plastic limit %
OL	29.8	39.8	30.4	3.04	2.66	20.6
KL	47.2	27.3	25.5	2.98	2.65	20.1

4.3.2 Compaction tests

Results for compaction tests to determine the optimum gravimetric moisture and maximum dry bulk density using two different rammer compacting weights and drop heights indicated significant** differences for optimum gravimetric moisture content and maximum dry bulk density (Table 4.4). Optimum moisture content (θ_{opt}) for the standard Proctor test was 19.1% at a maximum dry bulk density of 1.68 g cm^{-3}. θ_{opt} reduced to 14.3% for the modified compaction test (heavier rammer) with a maximum dry bulk density of 1.86 g cm^{-3}. This implies that the optimum moisture content and the maximum compaction differ with the magnitude of the compaction force or energy. Whilst this is intuitive it is of great importance in understanding roller selection. No significant difference was determined between the two soil types or air voids at optimum moisture (Table 4.4).

Table 4.4 Mean, LSD and significance (p = 95%) for Proctor test results.

	Optimum moisture content, θ_{opt} %	Dry bulk density g cm^{-3}	Air voids %
2.5 kg rammer	19.1	1.68	5
4.5 kg rammer	14.3	1.86	3.5
LSD	0.53	0.03	2.15
ANOVA F test p value			
Soil type	0.964	1.000	0.698
Rammer	<.001	0.002	0.095

Plotted results show all points with moisture content above the optimum to be between 0% and 5% air voids (Figure 4.8). It is unlikely that all air voids can be removed by compaction of this level because air will become trapped in soil micropores as dry bulk density increases limiting its movement and increasing the soil strength. This is in agreement with the DSIR (1951) who also determined minimum and optimum air voids at approximately 5% and also the Department of Transport (Department of Transport, 2006) who accept 5% air voids to be the achievable maximum for highway works.

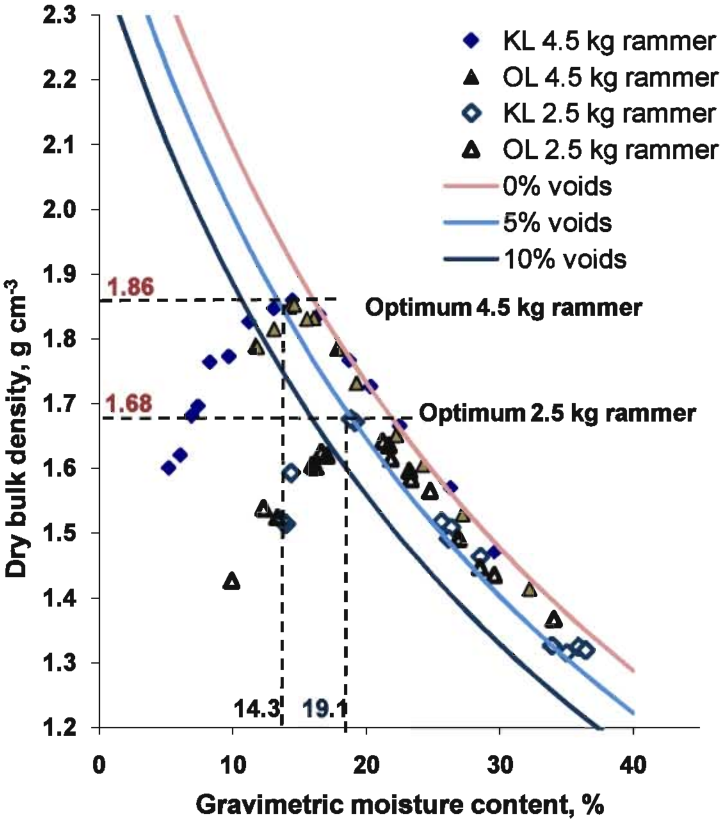

Figure 4.8 Standard and modified Proctor test results with lines indicating theoretical 0%, 5% and 10% voids, determined using Equations 4.1 and 4.2.

Optimum moisture (θ_{opt}) is below the plastic limit for both tests but relatively close for the standard Proctor test (within 1.5% gravimetric moisture content).

4.3.3 Shear strength parameters

Strength tests were carried out on the OL soil only and the results indicating variation in cohesion (c) and internal friction angles (ϕ) are summarised in Table 4.5.

Table 4.5 Summary of strength parameters and shear strength calculated from Equation 4.4. TSB - translational shear box; QU- quick undrained triaxial.

Soil	Gravimetric moisture content (%)	Test method	Cohesion (c) kN m^{-2}	Angle of internal friction (ϕ) degrees	Shear strength(τ) (σ = 100 kN m^{-2}) kN m^{-2}
OL	8	TSB	0.1	51.8	123.9
OL	15	TSB	30.8	41.1	120.5
OL	15	QU	35.2	33.0	96.6
OL	18	QU	27.2	19.4	62.4
OL	23	QU	31.6	5.9	41.9

In the translational shear box experiment, c was significantly* greater at 15% than 8% moisture content. In the triaxial shear experiment, there was a significant* decrease in ø as moisture content increased due to increasing lubrication by soil water, particularly as moisture content approached and passed the plastic limit of 20%. Whilst there was a significant* relationship between c and moisture content it was not consistent. The only direct comparison between the two test methods was for the soil at 15%; there was no significant difference in c and ϕ between methods. Shear strength decreased significantly* as moisture content increased although between 8% and 15% moisture this was not significant.

The plastic limit is passed as soil moisture increases and the reduction in friction reduces the overall shear strength. Rolling of soil whilst in a moisture state greater than θ_{opt} will require less force for plastic deformation however as a maximum dry bulk density for a particular applied force is reached the incompressibility of water will resist further compaction. Below the plastic limit soil will be more likely to suffer brittle failure and rolling with a force in excess of the soil shear strength may induce cracking as the soil fails.

At cricket pitch densities of 1.50 g cm^{-3}, similar to those tested in the strength experiments, the chance of shear failure when subjected to loads in excess of those shown in Table 4.5 is possible. However as the soil is rolled the increase in plastic deformation increases the dry bulk density, and effectively the confining pressure, and therefore the shear strength increases to a higher level. Excessive roller force could result in shear failure particularly at the edges of the roller and therefore gradual increases in bulk density from incremental increases in roller weight will reduce the incidence of damage to the playing surface.

4.3.4 Dynamic compaction

The effect of a dynamic load applied to prepared samples of soil at different densities and moisture contents indicated clear relationships of significance to the explanation of soil behaviour during rolling.

The relationship between successive dynamic loads of a similar pressure and the resultant reduction in volume displays characteristics that are similar in nature to an increasing load. Figure 4.9 presents results for a sequence of four repeated dynamic loads of approximately 100 kPa for three different soil moistures where volume strain is measured by change in dry bulk density (this is axial strain (as a percentage of total sample length) combined with changes in radial strain measured by radial transducers).

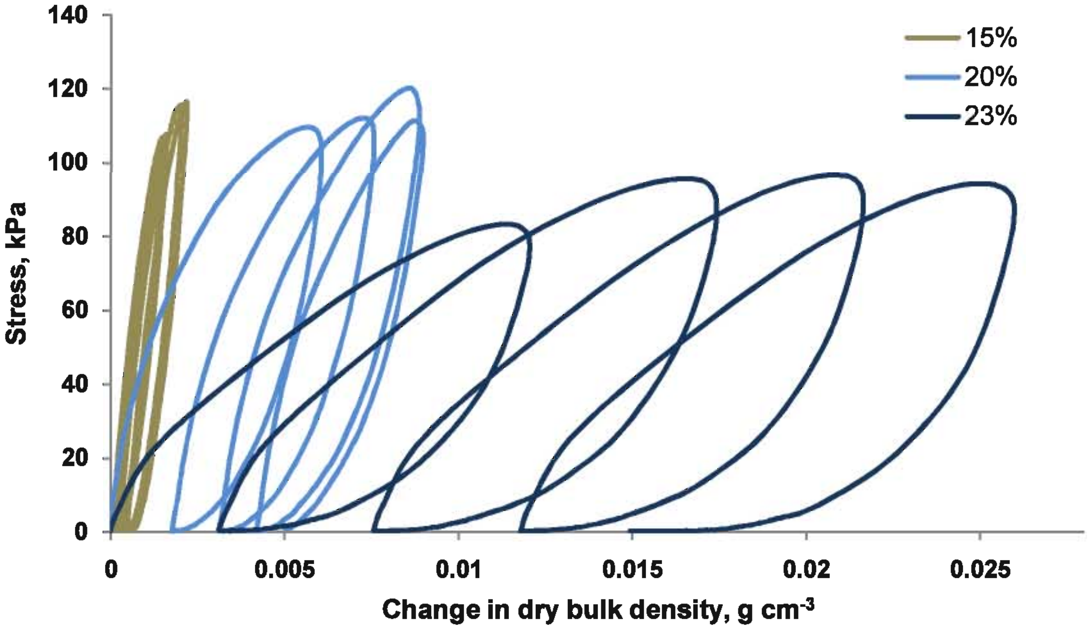

Figure 4.9 Stress / dry bulk density change relationship for the OL soil at a dry bulk density of approximately 1.60 g cm^{-3} for three different gravimetric moisture contents. Four successive dynamic stress loadings resulted in greater density change for higher moisture samples and a reduction in permanent density increase with successive loads.

Maximum strain and residual strain are greater for higher moisture samples as a result of reduced stiffness (Table 4.6).

Table 4.6 Dynamic stiffness (k_d) for four repeated loads of 0.5 s duration on soil samples with a dry bulk density of 1.60 g cm^{-3} with different moisture contents (as per Figure 4.9). Increase in stiffness occurred with a reduction in moisture content and with successive loads.

		Dynamic stiffnesses (k_d) in MPa		
Dry density, g cm^{-3}		1.6	1.6	1.6
Moisture content, %		15	20	23
Rep	1	93.77	17.82	11.09
	2	90.27	21.23	10.19
	3	104.56	30.96	9.82
	4	100.92	28.76	10.95

Dynamic stresses, which can be seen to simulate cricket roller passes, show a tendency towards a reduction in bulk density change with successive loads and an increase in soil stiffness however this was not consistent. This has also been shown for sand, sandy loam and clay loam soils, compacted to a range of densities, by Guisasola (2008). This occurs as a result of increasing shear strength and stiffness as soil bulk density increases indicating that a constant load will have a reduced propensity to compact with successive loadings in a particular soil physical condition.

Comparing stress / strain relationships between soil densities of 1.40 and 1.60 g cm^{-3} (Figure 4.10; Table 4.7) illustrates the difference in stiffness between soil densities.

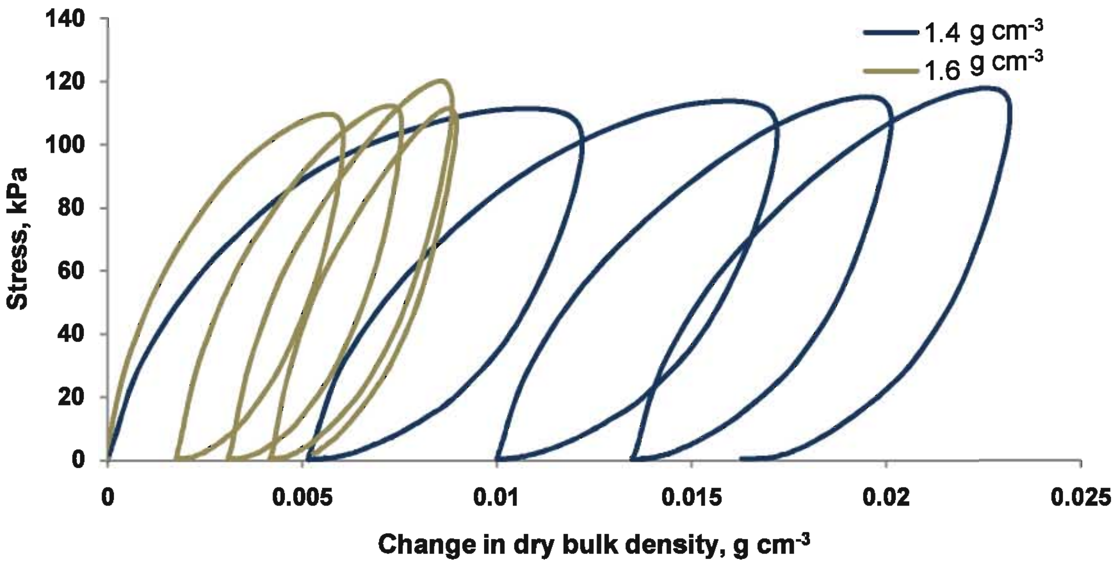

Figure 4.10 Stress/bulk density change relationship for OL soil at two densities, 1.40 and 1.60 g cm^{-3}, at 20% gravimetric moisture content. The lower density soil exhibits greater change in density for a similar load of 100 kPa. Both soils exhibit a reduced change in density with successive loading.

Table 4.7 Dynamic stiffness (k_d) for four repeated loads of 0.5 s duration on soil samples with a dry bulk density of 1.40 and 1.60 g cm^{-3} at 20% gravimetric moisture contents (as per Figure 4.10).

		Dynamic stiffnesses (k_d) in MPa	
Dry density, g cm^{-3}		1.4	1.6
Moisture content, %		20	20
Rep	1	13.98	17.82
	2	14.63	21.23
	3	17.72	30.96
	4	18.69	28.76

Four successive loadings of approximately 100 kPa indicated greater maximum change in dry bulk density as well as greater residual strain for the less stiff lower bulk density soil. Similar to Figure 4.9, a reduction in residual dry bulk density occurred with successive loadings and an increase in soil stiffness. Figures 4.9 and 4.10 shows the soil sample undergoing elastic hysteresis whereby more energy is required to increase the axial strain than is required for the soil to return to its new state. Energy is used for work done to achieve the change in dry bulk density and any residual energy is dissipated as heat. Recoverable elastic movement was measured in terms of maximum change in bulk density before elastic recovery. The results indicated a positive correlation with load (Figure 4.11). All tested levels of dry bulk density indicated that an increase in moisture content produced a greater maximum change in density for a given load stress due to reduced stiffness. As dry bulk density increased a higher load was required to achieve a given level of maximum change in density as a result of the greater soil stiffness.

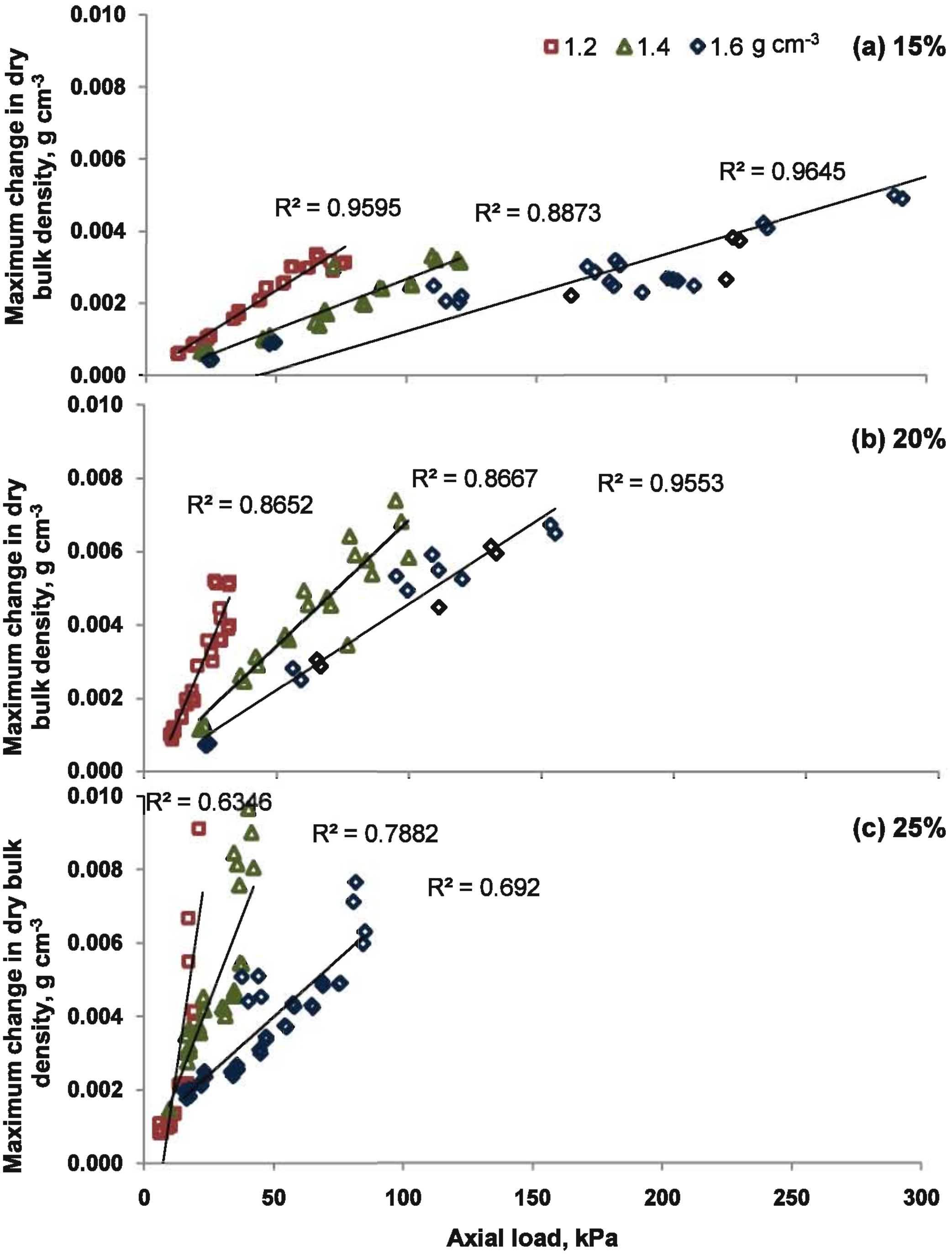

Figure 4.11 Maximum change in dry bulk density resulting from a load applied for 0.5 s. (a) 15%, (b) 20% and (c) 25% gravimetric moisture content; OL soil. An increase in density and/or a reduction in moisture content increase soil strength and reduce maximum density change for a given load. R^2 refer to the linear trendlines.

Soils with higher bulk density and lower moisture therefore require a greater load stress to instigate the same maximum soil movement due to the greater soil stiffness. The same principle was determined, though less consistently, for permanent plastic deformation resulting from a dynamic load (Figure 4.12).

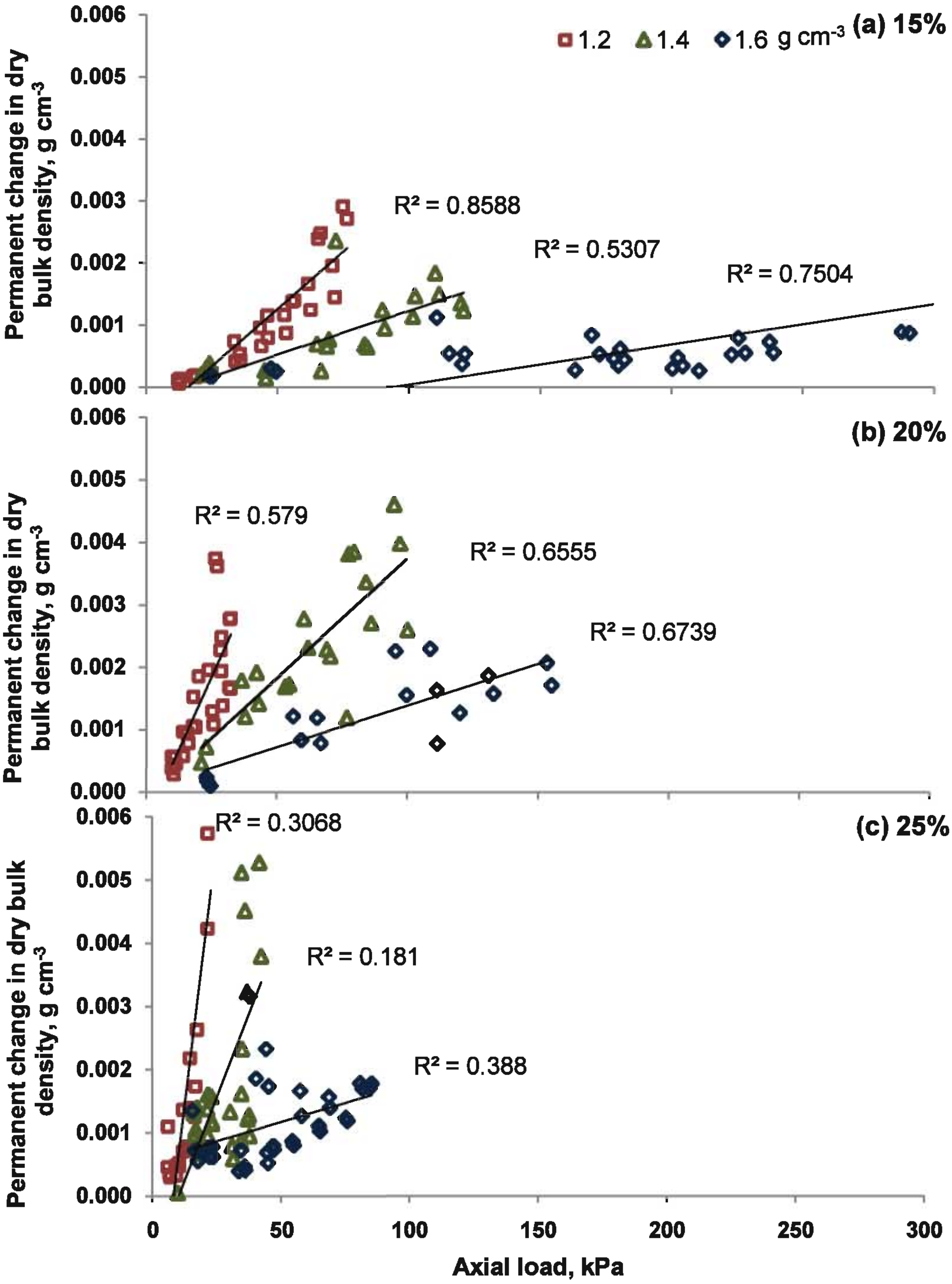

Figure 4.12 Permanent change in dry bulk density resulting from a load applied for 0.5 s. (a) 15%, (b) 20% and (c) 25% gravimetric moisture content; OL soil An increase in density and/or a reduction in moisture content increase soil strength and reduce permanent density change for a given load. R^2 refer to the linear trendlines.

Permanent change in dry bulk density will be reduced in soils with lower moisture content and a higher initial dry bulk density within the range of densities (1.20 to 1.60 g cm^{-3}) and moistures (15%, 20% and 25%) tested.

The permanent increase in dry bulk density (plastic deformation) resulting from the maximum change in dry bulk density (before elastic recovery) was greater for a lower starting density (Figure 4.13) and a higher moisture content (Figure 4.14).

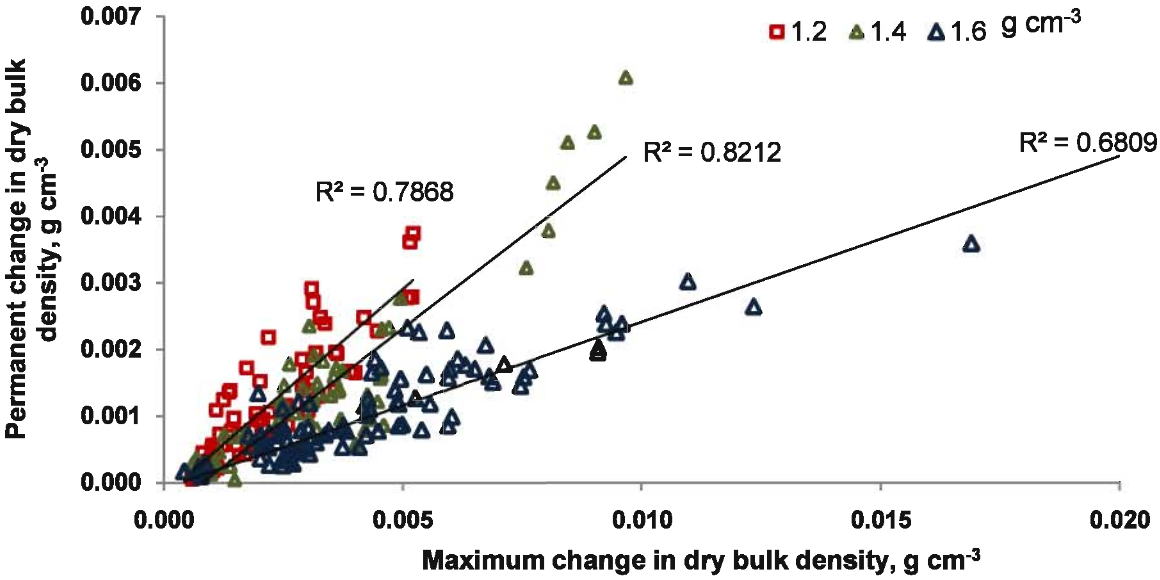

Figure 4.13 Permanent increase in dry bulk density resulting from maximum increase in dry bulk density before elastic recovery for three starting densities. R^2 refer to the linear trendlines.

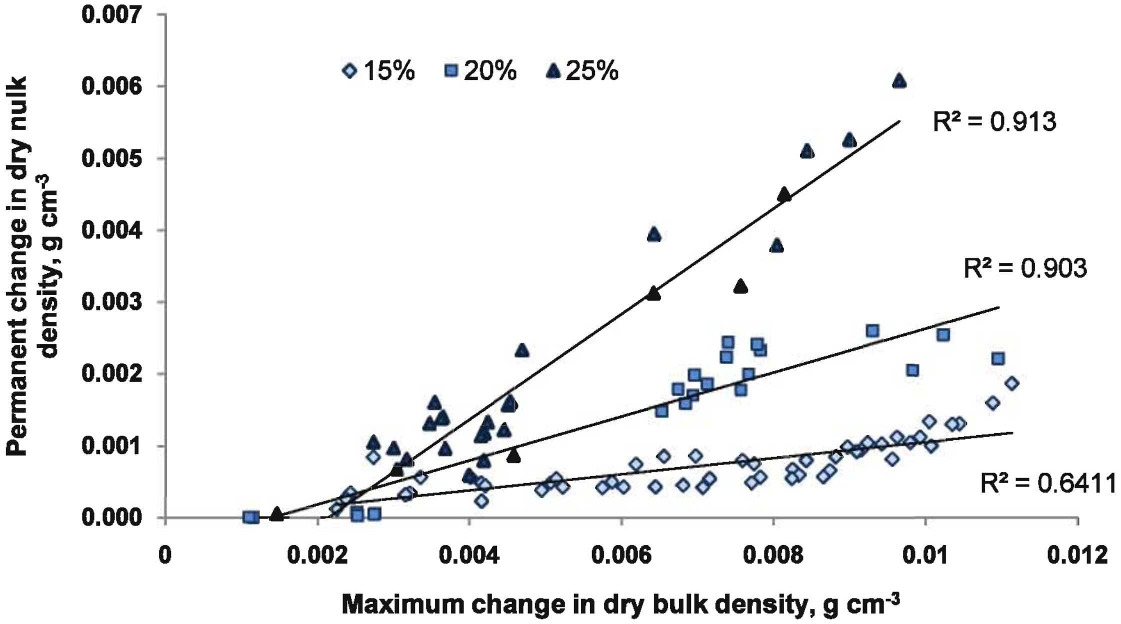

Figure 4.14 Permanent increase in dry bulk density resulting from maximum increase in dry bulk density before elastic recovery for different moisture contents. R^2 refer to the linear trendlines.

Lower soil strength resulting from higher levels of air voids in lower bulk density soils result in a more compressible soil with a reduced level of inter-particle soil skeleton contact therefore reducing strength. Increases in moisture content will reduce inter-particle friction and suction also reducing soil strength. Soil stiffness is increased with an increase in bulk density, reducing maximum and permanent strain under loading.

Rolling cricket pitches with low moisture content and/or a high dry bulk density will require a greater force to increase dry bulk density however as moisture content increases beyond the optimal level the soil air voids reduce and the soil stiffness will increase reducing compaction.

Dynamic load was increased to achieve an increase in dry bulk density of 0.005 g cm^{-3} (reasons explained in Section 4.2.4). Replicated samples were subjected to a statistical analysis of variance and the mean load stress for combinations of gravimetric moisture and dry bulk density are plotted in Figure 4.15. Significant** differences for required stress were determined for density and moisture combinations.

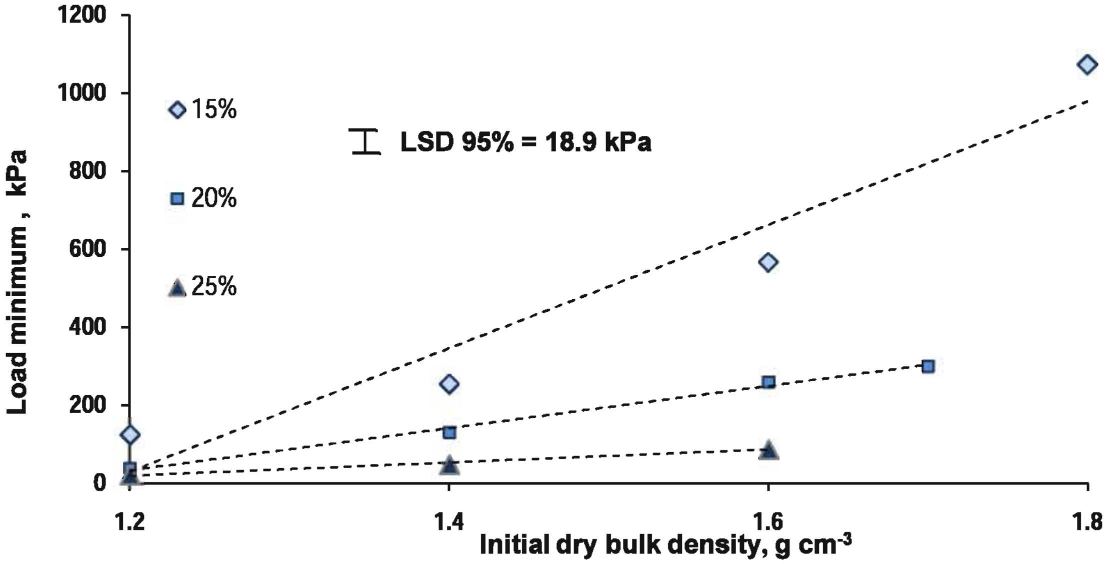

Figure 4.15 Minimum load requirement to increase dry bulk density by 0.005 g cm^{-3} for different gravimetric moisture contents. Dashed lines are linear trendlines and are described in Table 4.8.

The relationship between load requirement and increased dry bulk density with regard to initial density gave linear regression models for each of the moisture contents (Table 4.8).

Table 4.8 Linear regression models for minimum load requirement to achieve 0.005 g cm^{-3} for different moisture contents for OL soil with a dry bulk density between 1.20 and 1.80 g cm^{-3}.

moisture	Relationship	statistical fit
15 %	y = 1580.9x – 1867.10	$R^2 = 0.933$
20%	y = 541.05x – 615.80	$R^2 = 0.993$
25%	y = 166.75x – 180.68	$R^2 = 0.987$
Multiple regression	y = -227.68+(density*840.91)+(moisture* -38.20)	$R^2 = 0.665$

These relationships have limited data points and only apply to three moisture contents and therefore they are likely to prove unreliable in the assessment of the potential of a particular roller configuration to achieve an increase in dry bulk density in specified soil physical conditions (roller compactive potential). Improved analysis could be made through ANN (Artificial Neural Networks) which was outside the scope of this thesis. However the results underline the increase strength characteristics of soil with lower moisture content and a higher dry bulk density.

4.3.5 Soil bin experiment

Results for the soil bin rolling experiment are presented for each of the three roller depths measured. For the depth 0 – 50 mm significant* differences were determined for roller passes and between roller weights (Figure 4.16).

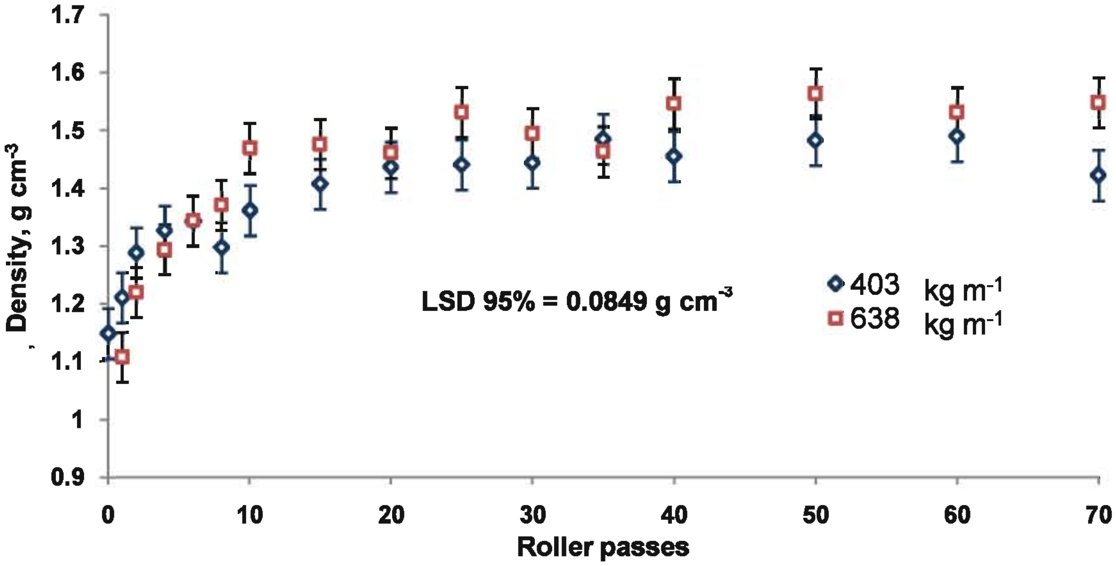

Figure 4.16 Change in dry bulk density with roller passes at 0 – 50 mm depth for two roller weights. Error bars indicate LSD 95%.

Dry bulk density increased significantly up to 10 roller passes. Soil dry bulk density had increased to 1.46 g cm^{-3} from 1.11 g cm^{-3} for the 638 kg m^{-1} roller and to 1.36 g cm^{-3} from 1.21 g cm^{-3} for the 403 kg m^{-1} roller. Between 10 and 70 passes there was no significant increase in dry bulk density however the density achieved by the heavier roller was significantly* greater. Bulk density reaches a maximum point where soil stiffness is too great for the roller pressure applied to be able to increase density any further.

Initial dry bulk density was low relative to cricket pitch densities due to the limitations of the soil bin processing equipment and therefore 10 roller passes may not be required in the field. The limitations of the soil bin equipment meant that the objective to determine the number of passes required was not achieved. However this data indicates that compaction may requires a number of passes when the roller compactive potential is high relative to soil stiffness but there is maximum number of passes above which continuing to roll with the same roller is ineffective and inefficient.

There were no significant differences in dry bulk density within a particular depth for measurements at depths 50 - 100 mm and 100 - 150 mm indicating that the compaction pressure reduced to below a significant compactive potential after 50 mm depth. However there were significant differences between depths which were a result of different initial densities. This could have been due to an increase in bulk density as a result of overburden stress or differences in profile preparation.

The mean soil shear strength for both rollers increased significantly** up to 25 roller passes for depth 0-50 mm and up to 15 passes for depths 50-100 mm. No significant increases occurred for depth 100-150 mm. Significant** differences were determined between depths (Figure 4.17). The greater initial strength at the lower depths was consistent with dry bulk density measurements with the same cause as indicated above.

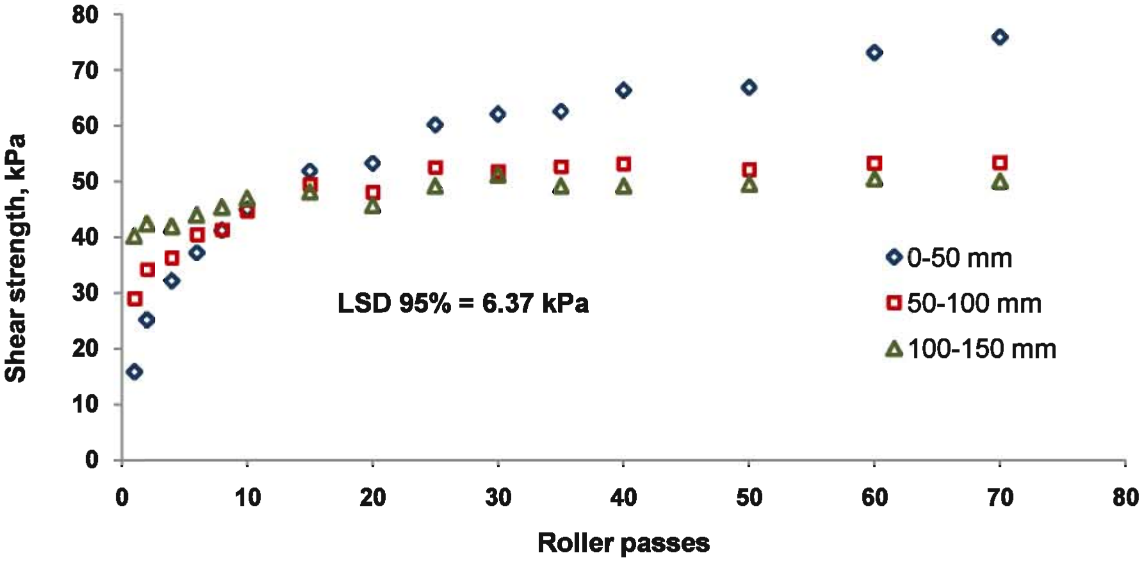

Figure 4.17 Shear strength (measured by shear vane) for roller passes at three depths. Mean of both roller weights. LSD 95% indicated within and between depths.

Increases in shear strength were not consistently significant between consecutive measurements and further increases after 25 passes (0-50 mm; and one pass 50-100 mm) were not statistically significant (Figure 4.18).

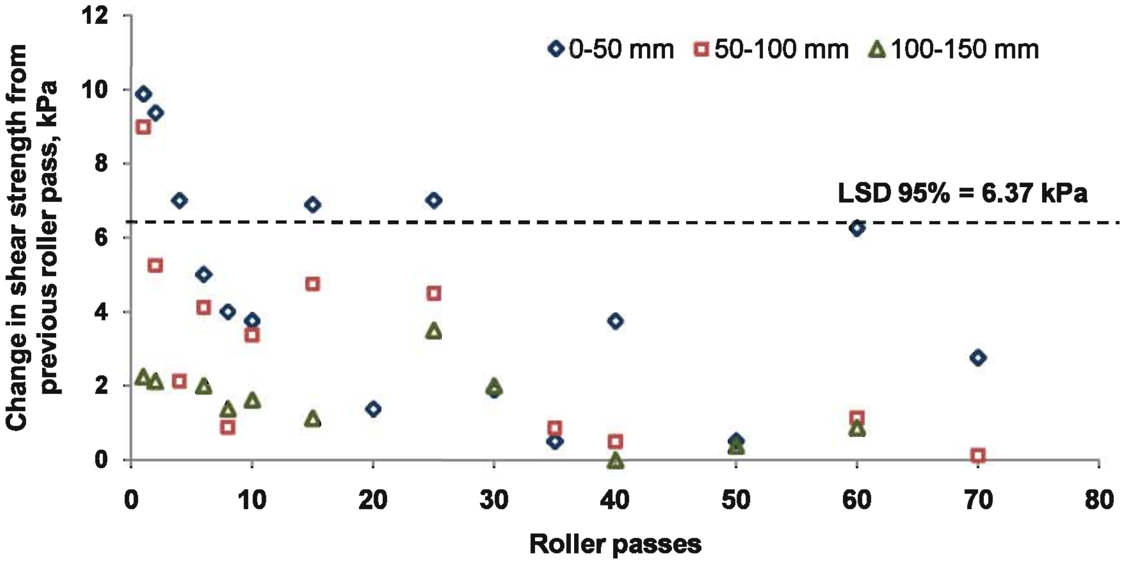

Figure 4.18 Change in shear strength (measured by shear vane) between consecutive roller measurements. Dashed line indicates LSD level.

Measurements indicated that there was a significantly** higher shear strength for the heavier roller from 20 passes up to 60 roller passes (Figure 4.19).

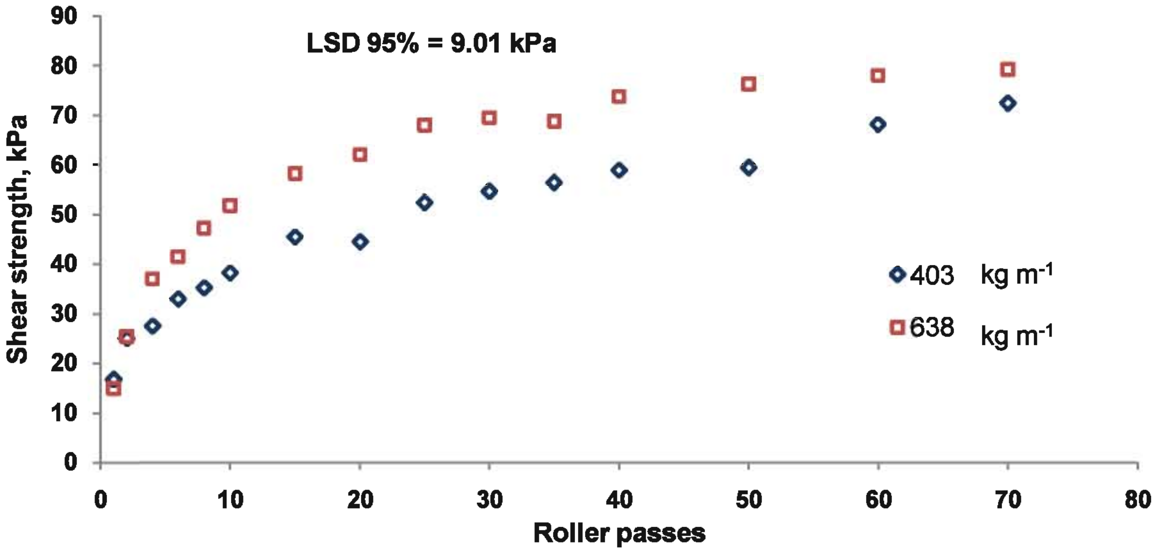

Figure 4.19 Shear strength for depth 0-50 mm for two roller weights.

Similarly there was significant** differences for the depths 50-100 mm from 20 passes until the end of the experiment (70 passes). There was no significant increase in shear strength for the depth 100-150 mm.

Moisture content was significantly** different between roller weights due to differences in profile preparation and this could have affected the shear strength and dry bulk density. Therefore this could have influenced the comparison between them.

Increases in strength measured by shear vane where no further increase in bulk density was determined could be as a result errors in dry bulk density measurement methodology, which was rectified in subsequent experiments, or could indicate that the shear vane is more sensitive to changes in bulk density for low density soils than the core sample method.

Static roller footprint measurements enabled the calculation of contact pressure. These indicated no difference in contact pressure for the first 20 passes but as soil stiffness increased roller indentation reduced and contact pressure increased for the 638 kg m^{-1} roller as the bearing capacity increased reducing roller footprint (Figure 4.20). The 403 kg m^{-1} roller did not have a significant change in contact footprint. This did not result in a further increase in dry bulk density measurements however there was an increase in shear vane measured strength beyond 20 passes for the heavier roller.

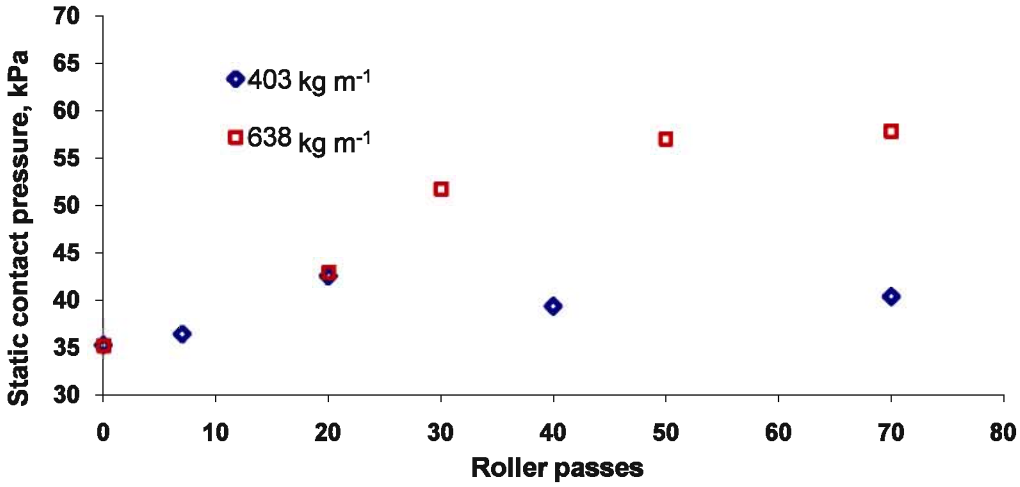

Figure 4.20 Theoretical contact pressure calculated from roller contact footprint

Speed treatments indicated no significant differences between treatments. It is likely that the differential between the two speeds was not great enough.

Draught measurement indicated a decline in force required between 1 and 70 roller passes for 1 km h^{-1} and a slight increase in force for 2 km h^{-1} between roller pass 1 and pass 70 for steady pull requirement (Figure 4.21).

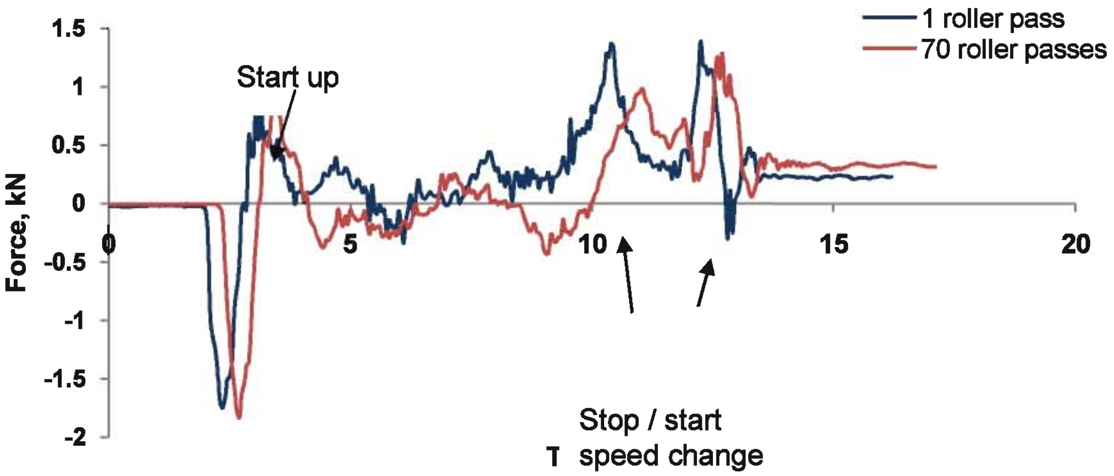

Figure 4.21 Draught force requirement for a towed 7.5 kN roller 1.2 m wide x 0.6 m diameter for start (1 roller pass) and end of experiment (70 passes). Initial start up is followed by a steady pull at 1 km h^{-1} followed by a stop start sequence before proceeding at 2 km h^{-1}. Results indicate a decline in draft force at 1 km h^{-1} between the passes and a slight increase in force for 2 km h^{-1}.

The differences between roller passes as well as speed were minimal compared to the start and stop forces recorded. Although rolling resistance is likely to reduce as soil stiffness increases and roller sinkage reduces, whether through elastic or plastic soil deformation, this was shown to be only a small change in these soil conditions. These data were used to indicate force requirements when designing the drive parameters for the cricket rolling simulator (Chapter 7).

The determination of change in soil porosity through water release characteristics indicated significant** differences in volumetric moisture content between zero and four roller passes. From four to ten passes the differences were significant** but not consistently at all levels of tension. No significant change occurred in volumetric moisture retention between 10 and 70 passes and no significant differences were determined between roller treatments (Figure 4.22).

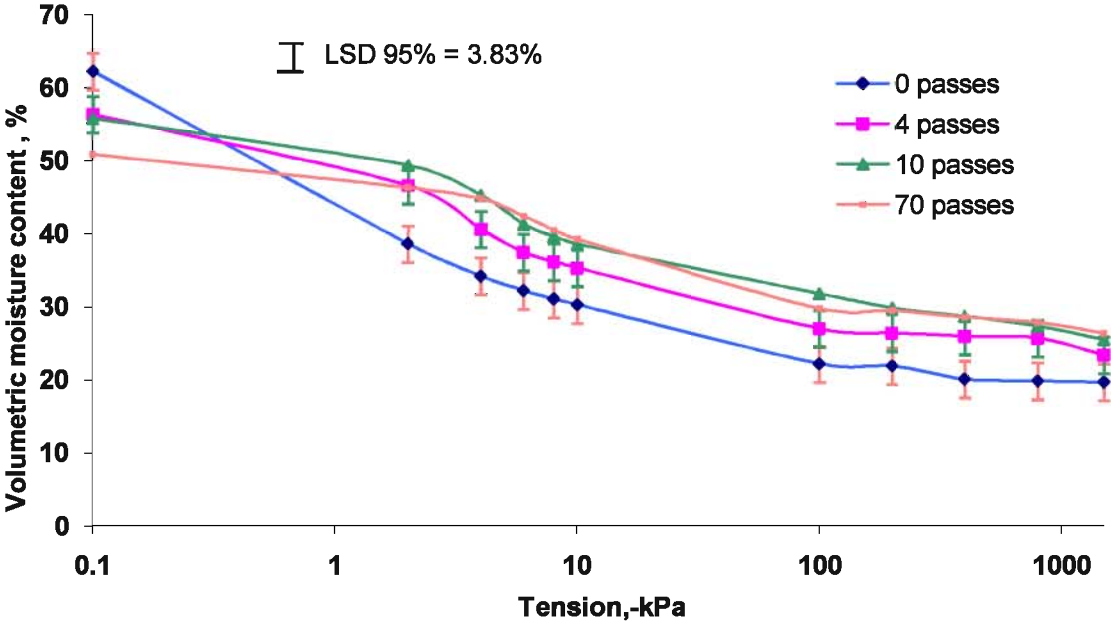

Figure 4.22 Water release characteristic curves for OL soil following different roller passes of a 403 kg m^{-1} roller towed at 2 km h^{-1}.

Differences in the volumetric moisture content indicate a change in the soil structure and a reduction in porosity resulting from an increase in soil bulk density. Roller passes beyond the first 10 had no affect on reducing soil porosity and the majority of any change occurred after four passes. These measurements were only taken at four roller pass intervals but are consistent with a gradual reduction in effectiveness from rolling.

4.4 Summary and discussion of soil characteristics

Soil physical and mechanical properties

Soil physical and mechanical properties for the two test soils were established. The results of the compaction tests indicated two different maximum densities at two different optimum moisture contents with the two different cumulative compactive loads, 1.68 g cm^{-3} at 19.1% and 1.86 g cm^{-3} at 14.3%. Air voids of 5% and 3.5% were similar to results produced by the DSIR (1951). Adams *et al* (2004) indicated target maximum dry bulk density of 1.65 g cm^{-3} to 1.75 g cm^{-3} (4% - 6% organic matter) (see Section 1.4) therefore the standard Proctor test (2.5 kg rammer) would be likely to give the best indication of compaction at this level which is in agreement with Parsons (1992). Although the impact force used to compact the soil in the Proctor test is not comparable to the force of a moving roller the resultant compacted soil with a minimum air voids between 0% and 5% could theoretically be replicated with a roller. The moisture at these levels of air voids and bulk density will be the same regardless of method of compaction. The target dry bulk density as laid down by Adams *et al* (2004) can be expressed in terms of a percentage of the maximum dry bulk density achieved in the standard BS compaction test using the method adopted by the transport research laboratory (Parsons 1992; Section 1.5.3.1) i.e. 1.65 and 1.75 g cm^{-3} are 98% and 104% respectively of 1.68 g cm^{-3} Proctor optimum of the OL and KL soils. However the maximum dry bulk density achievable by a roller may not be as high as the standard Proctor test achieve and therefore the optimum moisture content could differ.

The results of both the compaction and shear strength analyses illustrate the sensitivity of both properties to moisture content. In compaction, an increase in moisture content eventually reduces the effect of normal stresses due to the low compressibility of water. Shear strength tests indicated a reduction in maximum stress at failure as moisture content increased, largely due to reduced friction (ϕ). An increase in moisture content was shown to initially increase shear strength due to an increase in cohesion (between 8 to 15 % gravimetric moisture content, cohesion increased significantly*) caused by the interaction between clay particles and thin films of water. As soil moisture content increased above 15%, however, cohesion did not increase but friction between soil particles reduced significantly, reducing soil strength (ϕ decreased significantly* from

8 to 23%).[2] Large decreases in cohesion below 15% could result in a decline in playability as the cricket pitch soil will be more inclined to break up as the soil becomes more brittle as it shrinks. Minimum moisture was not established in this context because moisture contents between 8% and 15% were not investigated although cricket pitches are unlikely to be dried below 15% moisture in the UK not only due to the climatic conditions but also because the pitch playability would become unacceptable as a result of soil cracking.

Dynamic triaxial tests

Dynamic triaxial testing confirmed the sensitivity to moisture content by showing that an increase in moisture increases the elastic and plastic soil movement, for a given dry bulk density and applied load, resulting from a reduction in shear strength. The results also indicated that higher dry bulk density soils have less permanent increase in density after an applied load compared to lower density soils due to increased shear strength.

Repeated soil loading with a constant load indicated declining increases in dry bulk density with successive loadings due to increases in shear strength and soil stiffness resulting from the increase in soil bulk density.

These experiments determined that soil with higher shear strength requires a greater minimum load stress to increase dry bulk density which enabled a soil-specific relationship between minimum load stress and dry bulk density, for three levels of gravimetric moisture content appropriate to cricket pitch rolling, to be established. This model indicates substantially higher levels of pressure required to increase dry bulk density than the maximum stress at failure derived from shear tests. A gradually increasing load as applied in shear tests is not consistent with a quickly applied and then released dynamic load which occurs with a moving roller, furthermore the confining stresses are generally not comparable.

Dynamic tests did indicate small increases in dry bulk density at levels lower than the assumed minimum increase of 0.005 g cm^{-3} which could indicate some potential to increase dry bulk density by applying lower pressures than indicated in Figure 4.15

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[2] Proctor and shear strength results form the basis of a paper presented at the ISEA conference in Munich 2006 titled 'The mechanical behaviour of cricket soils during preparation by rolling' (Appendix 12).

however these small changes could also be caused by equipment and experimental noise.

Soil bin experiment

The soil bin rolling results indicated maximum dry bulk density to be 1.36 g cm^{-3} for the 403 kg m^{-1} roller and 1.46 g cm^{-3} for the 638 kg m^{-1} roller in the 0-50 mm depth. These were achieved after 10 roller passes. No increase in dry bulk density occurred at lower depths. Shear strength increased up to 35 passes for the 0-50 mm depth and to 15 passes for the 50-100 mm depth. Roller footprint for the two roller weights was the same up to 20 roller passes. Further increases in pressure calculated from roller contact footprint occurred with the 638 kg m^{-1} roller to 60 kPa at 50 passes but remained at approximately 40 kPa for the 403 kg m^{-1} roller. Treatments measuring differences in dry bulk density resulting from roller speed indicated no statistical difference.

This experiment provided a starting point for future experimental work. Reduction in soil compaction with successive passes was in agreement with previous work (Abebe *et al*, 1989; DSIR, 1951; Raghavan *et al*, 1976) although the amount of passes to achieve the maximum potential dry bulk density from the rollers used was not determined due to the limitations of the processing equipment in producing an initial bulk density equivalent to an established cricket pitch. Maximum compactive potential of the two rollers was determined for soil gravimetric moisture content of 20%. The soil profile was constructed 24 hours prior to use and was therefore not in the same physical condition as a pitch that had been subjected to natural change over time from climatic and biological influences. To get an improved understanding of the effectiveness of successive roller passes as well as the significance of speed, load and moisture and grass roots in the compaction of cricket loams it was considered that outside experimental plots needed to be constructed.

Chapter 5. Field experiments

5.1 Introduction

Procedures for practical rolling management of cricket pitches will need to be a refinement of current practice and based on an improved scientific understanding of compaction of cricket soils. Laboratory experiments characterising soil mechanical properties provide the basis for the understanding of soil compaction but do not accurately represent cricket pitch physical or environmental conditions. To transfer the understanding of soil mechanical properties, and their influence on the effectiveness of rolling under different soil physical conditions, controlled field experiments were necessary. Field trial plots allowed for a one year period of soil aggregation and consolidation resulting from the natural influence of climate and soil moisture changes before being rolled (typical in normal cricket pitch construction) as well as the interaction of grass roots within the soil profile.

Soil moisture content is crucial to the effectiveness of compaction as well as cricket playability. Natural drainage is limited in compacted clay soils and therefore the reduction in moisture is largely a result of plant transpiration and surface evaporation. Summer pitch preparation timing is dependent on drying times which were measured by moisture sampling on the field experimental plots.

5.2 Field experiments: methodology

Using actual cricket grounds for experimental work was considered to have its limitations and generally unpractical for the project. Intensive soil sampling causes damage to a pitch affecting playability and control over the rolling management would not be possible. To run effective experiments to establish rolling protocols in an environment similar to a cricket pitch, trial plots were constructed in May 2005.

5.2.1 Construction

The proposed site at the Silsoe campus was surveyed (Appendix 6) and contractors were then employed to excavate the site, install drains and help construct the plots. The total plot area was 13 m x 8 m and excavated a minimum depth of 250 mm to enable a level area to be constructed on a slightly sloping site. A base layer of minimum 50 mm coarse sand was overlaid with 200 mm of compacted loam laid in 4 x 50 mm layers. Compaction was achieved with the use of a vibrating plate and manual 'heeling in'. The plot area was seeded with Rigby Taylor R9, a perennial ryegrass (*Lolium perenne*) mix of dwarf varieties (40% Ace, 20% Tucson/Green cup, 20% Greenflash, 20% Greenway) at 35 g m^{-2} and grass management throughout the experiment in the following three years was in accordance with standard cricket practice (ECB, 2007).

Two soils were used, OL and KL (as detailed in Section 4.2.1) and constructed in opposing corners (Figure 5.1). This layout allowed for a total of 10 individual plots 1.3 m x 4 m for each soil type and allowed for a rolling treatment to include both soil types within a rolled strip (Figure 5.2).

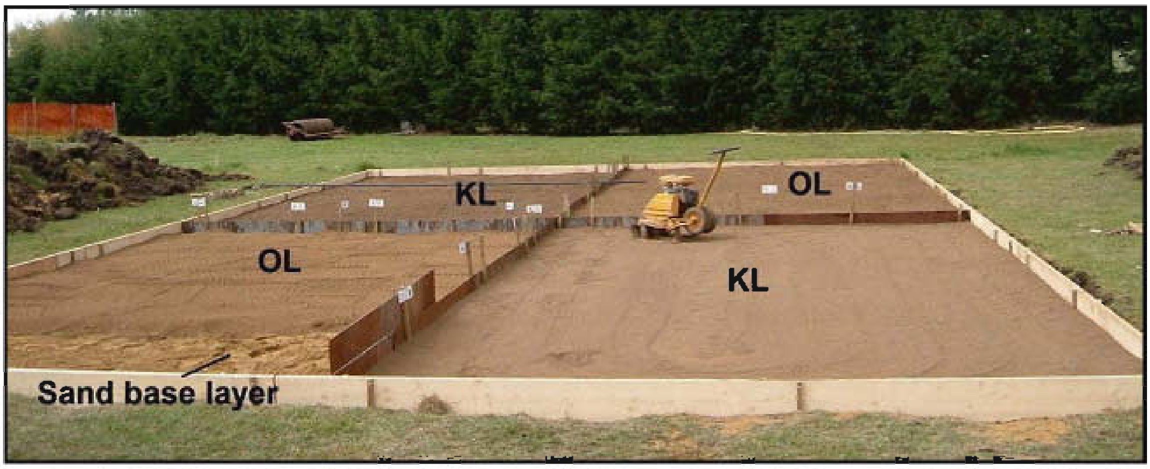

Figure 5.1 Trial plots during construction May 2005. Two soils Kettering Loam (KL) and Ongar Loam (OL) were laid in opposing corners enabling 10 individual plots for each soil. Rolling was undertaken in 10 rolled strips 1.3 m wide (from left to right / right to left in this picture) covering both soil types.

5.2.2 Experiment descriptions and rationales

Experimental work on the field plots was conducted to establish the maximum achievable dry bulk density from two roller weights under naturally occurring soil moisture contents in the spring and for manipulated moisture contents (by irrigation) in the summer. This was achieved in a similar manner to a Proctor test by establishing a maximum dry bulk density achievable with a given force/stress at a specific moisture content. Although rolling will affect the soils drying potential and therefore shrinkage (which will in turn influence the dry bulk density achieved) the potential of a roller to compact a soil of a specific dry bulk density essentially are the criteria required by the rolling guidelines. Final densities achieved from a pitch management protocol combining rolling and drying were not the main aim of the experimental work however certain comparisons between rolling procedures were possible.

In addition to the basic experimental work to determine the roller compactive potential, experiments examining roller speed, roller passes, pitch drying and pitch playability were undertaken. Current spring rolling practice for most cricket clubs is to start rolling pitches from early spring (February/March) at higher moisture levels than the Proctor optimum and to continuing rolling (at various combinations of roller weight, speed and passes) as the soil moisture reduces until late spring (end of April). Current practice was assessed by the survey of ground staff (Section 3.2) and review of the ECB standard manual TS4 (ECB, 2007).

Five separate experiments were undertaken during spring and summer in 2006 and 2007 to inform Objectives 3 and 4. This section provides an overview and aims and objectives of the experiments. Table 5.1 provides an outline of experiments and Appendix 7 provides full details of all experimental parameters.

Table 5.1 Field experiment rolling parameters.

Exp	Date	Parameters assessed	Treatment	Roller passes, no.	Roller mass, kg m^{-1}	Speed, km h^{-1}
1	Spring 2006	Roller mass; Early spring moisture	1	60	725/920	0.7
2	Spring 2006	roller mass; Late spring	1	28	920	0.7
3	Summer 2006	Continuation of Exp 1 in drier conditions	1	30	920	0.7
4	Spring 2007	Two roller speeds, spring moisture	1	18	920	0.7
			2	18	920	0.35
5	Summer 2007	Pre-match wetting and 14 days drying	1	28	920	0.35
			2	30	920	0.35

Experiment 1 – Spring rolling multiple rolling sessions

This experiment aimed to determine the maximum compactive potential of two roller weights under spring soil physical conditions. Multiple sessions are current normal practice aimed at achieving a gradual increase in bulk density through the spring period.

Six separate rolling sessions were conducted at approximately 14 day intervals depending on weather conditions (no pitch covering took place) totalling 60 roller passes. Two roller masses were used; 725 kg m^{-1} for sessions1, 2 and 3 and 920 kg m^{-1} for sessions 4, 5 and 6.

Prior to this experiment 10 passes of all plots with a 130 kg m^{-1} roller (grass mower) occurred. Gravimetric moisture and dry bulk density results were recorded before and after and no change in dry bulk density was determined for any of the plots.

Experiment 2 – Spring rolling single rolling session

This experiment was for a single session of rolling later in the spring to determine if the multiple session treatment had any additional benefits to dry bulk density or soil moisture content. This experiment conducted one roller session of 28 passes undertaken at the same time as session 5 of Experiment 1. Comparisons between Experiment 1 and 2 were made.

Experiment 3

Experiment 3 aimed to roll in conditions closer to Proctor optimum unlike experiments 1 and 2 and was conducted in the summer of 2006 in order to continue to determine the maximum compactive potential of the 920 kg m^{-1} roller in drier soil. This experiment used the same plots that had been used in Experiment 2 for the 'single session' rolling treatment (April 24th - 27th 2006). Two sessions of 15 roller passes each were conducted.

Experiment 4

Roller speed is an unknown factor in cricket pitch rolling and has previously only been discussed in terms of 'fast' or 'slow' with no actual measure suggested. This experiment was designed to compare the compactive potential resulting from two roller speeds 0.7 km h^{-1} and 0.3 km h^{-1}, with a 920 kg m^{-1} roller in three sessions of six passes at suitable intervals during March/April 2007.

Experiment 5

Summer pitch preparation techniques vary widely but with the same aim of maximising pitch bulk density. Pitches are often rewetted prior to rolling (Figure 5.2) with this process starting up to three weeks before play. ECB guidelines (ECB, 2007) recommend saturation of the playing surface to 100 mm at the start of the pitch preparation process which should occur at 'no less than 10 days prior to the match'. This experiment was designed after survey results had been analysed (Section 3.4.1) to emulate common practice with three different treatments to determine a procedure for summer pitch preparation prior to match use. Treatments are outlined in Table 5.2.

Table 5.2 Treatment criteria for Experiment 5. Roller passes with a 920 kg m^{-1}, 2 drum roller (600 mm diameter) driven at 0.35 km h^{-1}.

Treatment	Moisture	Rolling regime	Total roller passes
1 'Daily rolling'	Saturate 14 days pre-match	Roll after 1 day (4 passes) and then daily (2 passes) for 12 days	28
2 'Reduced rolling'	Saturate 14 days pre-match	Roll after 1 day (6 passes) then 6 passes every 3 days (days 11,8,5,2 – before' match day')	30
Control	Saturate 14 days pre-match	No rolling	No passes

Figure 5.2 Irrigation of plots to saturation for Experiment 5, 2006 (left). Rolled strips during Experiment 5 (right).

All experiments used three rolled strips per treatment utilising six plots resulting in three replicate plots per soil type. Control plots were also tested to determine the change in dry bulk density resulting from natural shrinkage from drying without rolling.

All plots were irrigated over the two days before rolling began (Figure 5.2). 80 mm of water was applied in four 20 mm applications taking approximately 2 hours per application giving an application rate of 10 mm h^{-1}.

5.2.3 Experiment measurements

A 1978 Whites AutoRoller (Autoguide, Calne, Wiltshire, UK) was used for all plot experiments. Designed specifically for cricket, the roller had two 600 mm drums, 1200 mm wide and weighed 1740 kg (Appendix 7 and 11). Water ballast was added to the drums to provide the additional mass required for the 2200 kg roller (Figure 5.3). This resulted in two roller mass treatments, 725 kg m^{-1} and 920 kg m^{-1}.

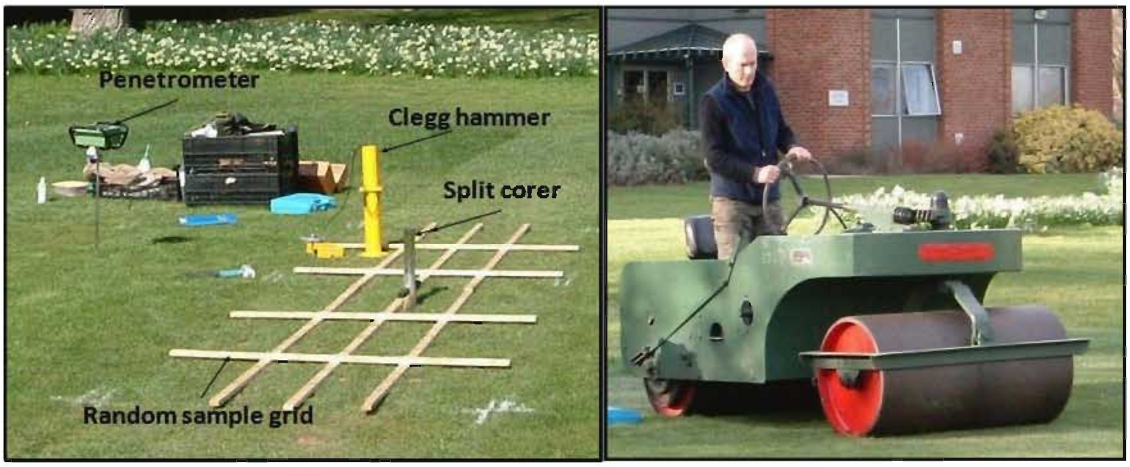

Figure 5.3 Cricket plot testing equipment, penetrometer, Clegg hammer, split corer and random sample grid (left). Roller used for all plot experiments, a 1978 White's Autoroller (Autoguide, Wiltshire) 1740 kg ballastable cricket roller (725 kg m^{-1} to 920 kg m^{-1}); 1200 mm wide with 600 mm diameter drums.

A combination of the following measurement techniques were used for the plot experiments and the actual measurements used for each experiment are detailed in Appendix 7:

- 150 mm soil cores were removed using a 42 mm split corer (BMS Products Ltd, Luton, UK). Samples were cut into five 30 mm lengths, re-measured for volume with vernier callipers, weighed and oven dried at 105°C to determine dry bulk density and moisture content. Two cores were taken from each plot for each sample interval resulting in six replicates for each soil treatment. The location of random tests was facilitated by the use of a moveable grid (Figure 5.3).

- Five measurements of rebound hardness were taken for each plot with a 0.5 kg Clegg Impact Hammer (Clegg, 1976) dropped from 0.55 m height at the same sampling interval as the soil cores.
- Shear vane measurements for 3 depths (50 mm, 100 mm and 150 mm) were taken in experiments when soil conditions allowed i.e. when the soil was moist enough to allow for adequate penetration and readings were not beyond the equipment limit. Sampling was undertaken close to the soil core extraction.
- Three penetrometer readings (using an Eijkelkamp Penetrologger with a 30°, 130 mm^{-2} base area cone at 30 mm s^{-1}) per plot at each sample interval when conditions allowed (as with shear vane) to determine indentation hardness.
- Vertical ball rebound height was measured from a ball dropped from 3 m 10 times on each plot during Experiment 4. Soil crack dimensions were also measured daily for all plots and allocated a score according to Table 5.3. The analysis of these two measurements was made in conjunction with dry bulk density and gravimetric moisture content sampling to gain an improved understanding of the relationship between moisture, cracking and ball rebound.

Table 5.3 Score allocation for pitch cracking.

Score number	Crack criteria description
0	No cracks
1	< 5 fine cracks, no longer than 100 mm
2	> 5 fine cracks and/or longer than 100 mm
3	Cracks > 2-3 mm wide + fine cracks
4	< 5 cracks > 5 mm wide+ fine cracks
5	< 5 cracks > 5 mm wide but no fine cracks
6	> 5 cracks > 5 mm wide + 2-3 mm cracks + fine
7	> 5 cracks > 5 mm wide but no fine
8	Very large cracks > 10 mm + fine
9	Very large cracks > 10 mm - no fine

Analysis of data was subjected to a statistical analysis of variance to a significance level of $p < 0.05$ and regression analysis was conducted on the cracking data and other data where appropriate.

Air voids were calculated using Equation 5.1.

$$\text{Air voids \%} = 1 - \left(\frac{\theta_m}{\rho_d}\right) + \left(\frac{\rho_d}{\rho_s}\right) \qquad \textbf{[5.1]}$$

5.2.4 Winter change in dry bulk density and gravimetric moisture content

The bulk density of a cricket pitch could change due to the swelling and shrinking resulting from winter precipitation and from frost heave. Although beyond the groundsman's control, any changes will affect the initial bulk density for rolling the following spring and will influence rolling recommendations. To study this effect soil cores were removed (using the same method as in Section 5.2.3) before and after the winter for two years during the project to determine winter-related changes in dry bulk density.

5.3 Results of field experiments

The results of the field experiments are presented and analysed by experiment (1-5) for changes in dry bulk density and air voids. Measurements that encompassed all experimental work on the trial plots are discussed following this and include cricket pitch playability and soil strength measurements.

5.3.1 Field Experiment 1 - Spring rolling multiple sessions,

Differences in dry bulk density between the two soil types were significant* but not in a consistent manner. Significant** increases in dry bulk density occurred for both soils over the experimental period although this was a result of a combination of rolling and shrinkage from soil drying. Comparison of control results with rolling treatment indicates the overall increase in dry bulk density from rolling although some additional drying occurred in the rolled plots indicating the likelihood of greater shrinkage. To determine roller compaction potential the initial dry bulk density of each session is crucial (Note: the first data point for each session was measured before rolling and after a period of rest where moisture content change may have occurred). Roller compaction potential is relative to the initial bulk density and moisture content and the results were analysed to determine potential increases from the roller mass for each moisture/dry bulk density scenario. Figure 5.4 presents the results for KL and OL soil.

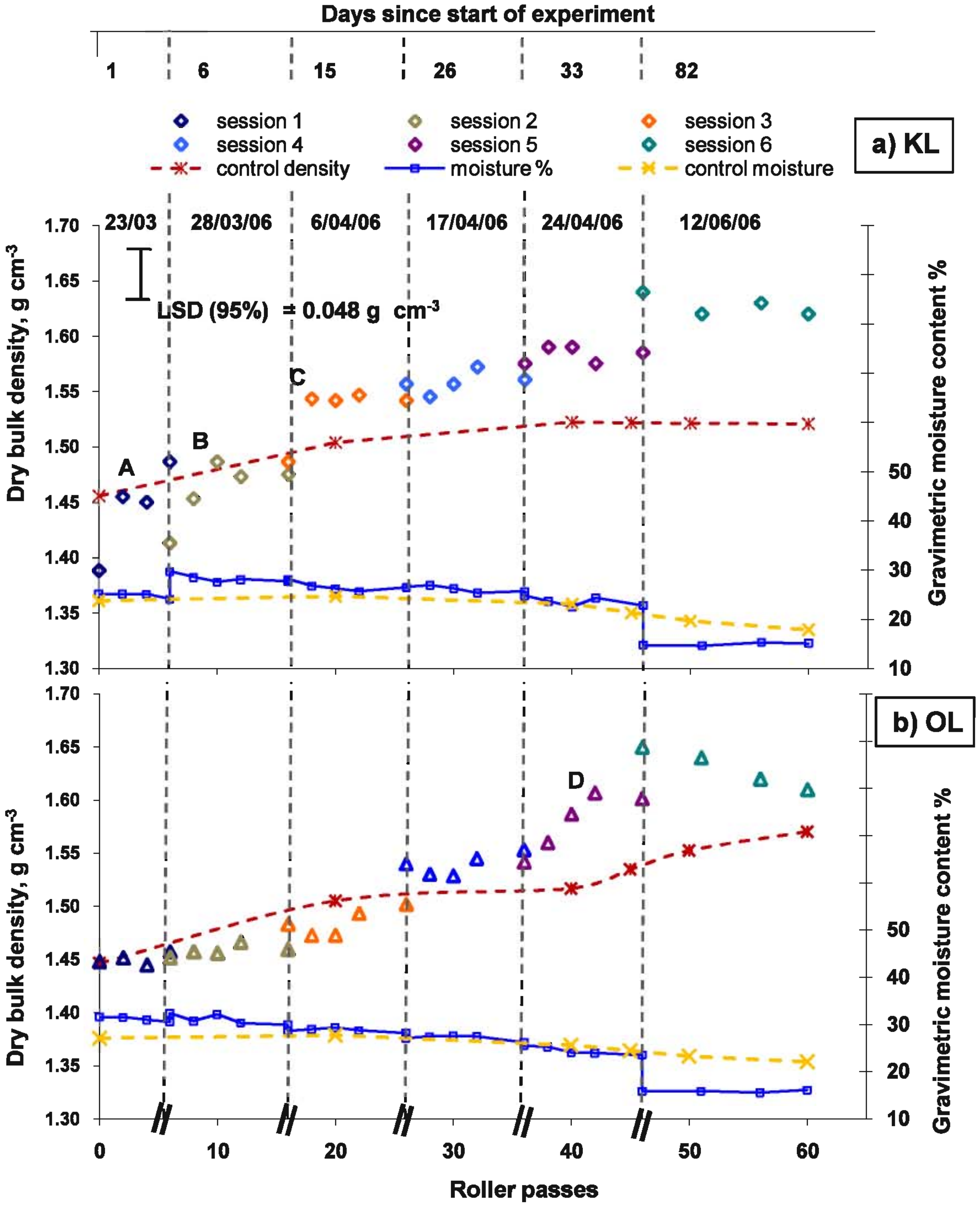

Figure 5.4 **Experiment 1 'multiple sessions'. KL soil (a) and OL soil (b), depth 0-60 mm using a 725 kg m^{-1} roller (600 mm diameter) for sessions 1, 2 and 3 and a 920 kg m^{-1}roller (600 mm diameter for sessions 4, 5 and 6. || indicates time break between roller passes and account for abrupt changes in soil gravimetric moisture content. Note: The first data point for each session was measured before rolling. Significant* increases in dry bulk density occurred during rolling sessions 1, 2 and 3 only (points A, B and C) KL soil and during session 5 (point D) OL soil. Other significant increases in dry bulk density were a result of soil shrinkage when drying. Control measurements indicate a significant** increase in dry bulk density from the rolling treatment compared to no rolling after session 2 (KL) and session 3 (OL).**

Results for KL soil indicated:

- Significant* increases in dry bulk density for each of Sessions 1, 2 and 3 (A, B, and C on Figure 5.4) but no significant increase for sessions 4 and 5.
- Breaks between roller sessions resulted in changes in soil moisture with a resultant change in soil dry bulk density.
- No significant increase in dry bulk density was determined for roller passes for the 920 kg m^{-1} roller used in Sessions 4, 5 and 6.
- Control measurements indicated a significant** increase in dry bulk density for the rolling treatment compared to no rolling from session 3 onwards; with a lower moisture for the rolled plots in Session 6 increasing dry bulk density from shrinkage.
- No significant increase in dry bulk density occurred after two roller passes (of a 2 drum roller) for Session 1, four roller passes for Session 2 and two roller passes for Session 3.
- Maximum dry bulk density achieved from the roller compactive force in the first three sessions with a 725 kg m^{-1} roller was 1.54 g cm^{-3} for the KL soil (point C Figure 5.4). However increases attributable to rolling and soil shrinkage due to drying resulted in a final dry bulk density of 1.64 g cm^{-3}.

Results for OL Soil indicated:

- No significant increase in dry bulk density during Sessions 1, 2, 3 and 4 due to rolling.
- A significant* increase in dry bulk density occurred during Session 5 whilst using the 920 kg m^{-1} roller and a maximum of 1.61 g cm^{-3} dry bulk density (point D Figure 5.4). This required 6 passes for roller Session 5). Final dry bulk densities attributable to rolling and soil shrinkage due to drying resulted in a final density of 1.65 g cm^{-3}
- Control measurements on the OL soil indicated significantly* higher dry bulk density for the rolled plots as a result of the increase in density achieved in Session 5 and due to the reduced moisture content in Session 6 increasing dry bulk density from shrinkage.

Increase in dry bulk density (or not) resulting from rolling can be largely explained from the level of air voids within the soil (Figure 5.5). For the rolling sessions that achieved an increase in dry bulk density whilst using the 725 kg m^{-1} roller the soil started with at least 4% air voids and for the 920 kg m^{-1} roller 2.4% air voids.

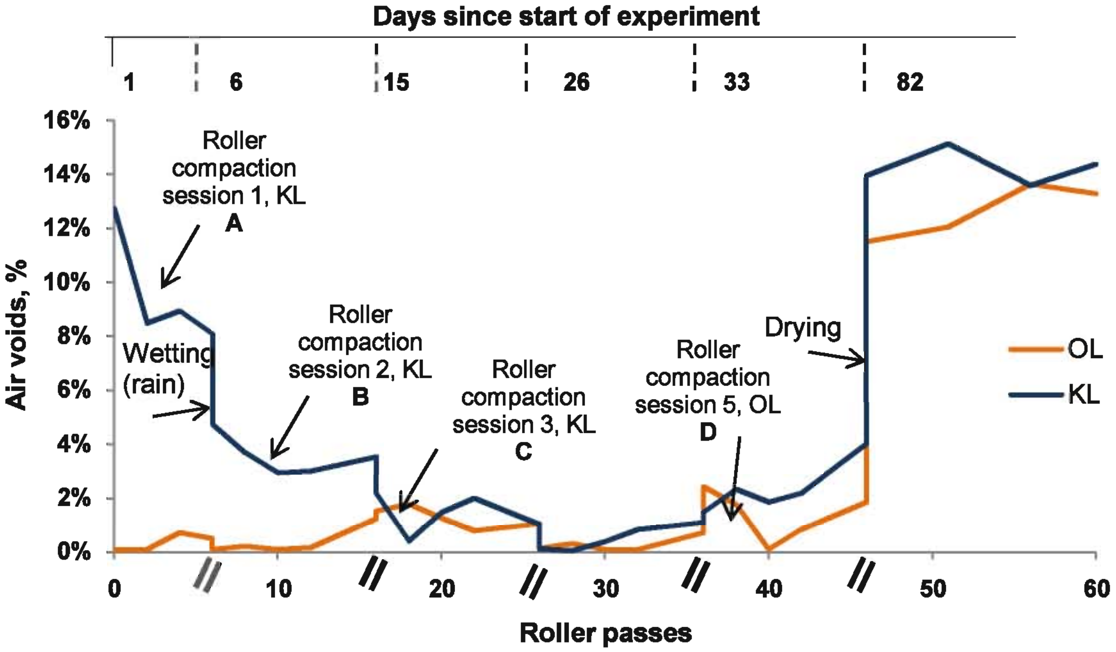

Figure 5.5 Soil air voids for KL and OL soils during Experiment 1 'multiple sessions' for the depth 0-60 mm. || indicates time break between roller passes. The relationship to increase in soil dry bulk density in Figures 5.4 is indicated by A, B, C and D.

Explanation of air voids for KL soil:

- KL soil has lower clay content and a greater median particle size resulting in increased drainage therefore the initial moisture content was lower than OL soil.
- KL soil dry bulk density increased during Sessions 1, 2 and 3 whilst the soil had adequate air voids for compaction (>2%) (Parsons, 1992).
- After Session 3 the air voids were below 2% and no subsequent increase in dry bulk density was achieved in Session 4.
- By Session 5 soil drying had increased air voids slightly (to 2%) however use of the heavier roller did not increase dry bulk density any further. The soil was at a dry bulk density of 1.59 g cm^{-3} at this stage with a gravimetric moisture content of 24%.

- Further drying before Session 6 due to a time break of 49 days reduced moisture content and increased air voids; however dry bulk density was not increased by further rolling in these soil physical conditions with the soil culminating with a maximum dry bulk density of 1.64 g cm^{-3} at 16% gravimetric moisture content.

Explanation of air voids for OL soil:

- No increase in dry bulk density as a result of rolling until Session 5 when the air voids increased to 2.4% due to drying. Some increase in density had occurred as a result of drying before rolling Session 4. At this stage the soil dry bulk density was 1.54 g cm^{-3} with a gravimetric moisture content of 24%.
- Rolling increased the dry bulk density to 1.61 g cm^{-3} after 6 roller passes of the session (42 passes overall). Further drying increased dry bulk density to a maximum of 1.65 g cm^{-3} but no further increases in density were determined by rolling.

Indications from roller weight for both soils:

- For both soils the 920 kg m^{-1} roller could not increase dry bulk density above 1.61 g cm^{-3} when soil gravimetric moisture content was at 24% in the depth 0-60 mm.
- For the 725 kg m^{-1} roller KL soil was increased to a maximum dry bulk density of 1.54 g cm^{-3} at gravimetric moisture content of 26%, depth 0-60 mm.
- The dry bulk density for the OL soil was not increased by the 725 kg m^{-1} roller and this indicated that the soil at less than 2% air voids could not be increased by this roller configuration whilst at dry bulk densities between 1.45 g cm^{-3} and 1.55 g cm^{-3}.
- No significant increases in bulk density below 60 mm were determined.

When the dry bulk density of the rolling treatment is compared to that of the control data there is clearly an overall benefit from rolling by the end of the experimental period (23/3/06-12/06/06). The maximum dry bulk density for the rolled plots was 0.11 g cm^{-3} higher than the control plots for both soils. Final dry bulk density of the soil profile is a result of the compactive effect of the roller, the background shrinkage effect of drying and the shrinkage effect of roller-compaction-induced drying. The control data indicates the background shrinkage effect of drying and therefore the additional increase in dry bulk density from rolling i.e. the marginal effect of rolling, is a combination of the compactive effect of rolling and the shrinkage effect of roller-compaction-induced drying. The benefit of rolling over and above natural soil drying and shrink is illustrated in Figure 5.6.

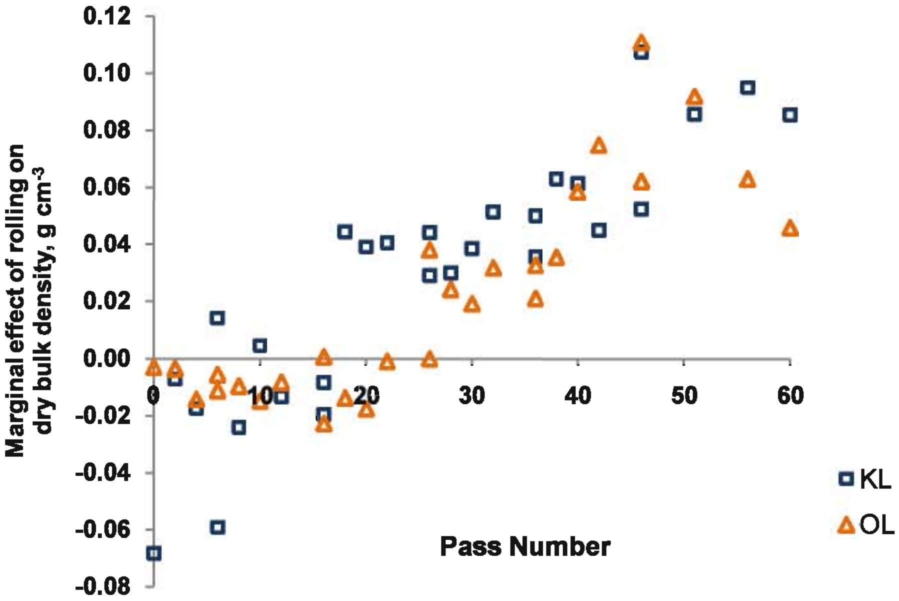

Figure 5.6 The marginal benefit of increased dry bulk density from rolling over and above the natural soil shrink and swell during the experimental period 23/03/06-12/06/06. The marginal effect is the combination of the compactive effect of rolling and the shrinkage effect of roller-compaction-induced drying.

5.3.2 Field Experiment 2 - Single session

Experiment 2 assessed increases in dry bulk density from a single roller session of 28 roller passes of a two drum roller. This procedure took four days to complete and therefore some soil drying occurred during the experimental period. The results of this treatment for both KL and OL soil are presented in Figure 5.7. Significant** differences were determined between soil type for much of the duration of Experiment 2 although initial dry bulk density was not significantly different.

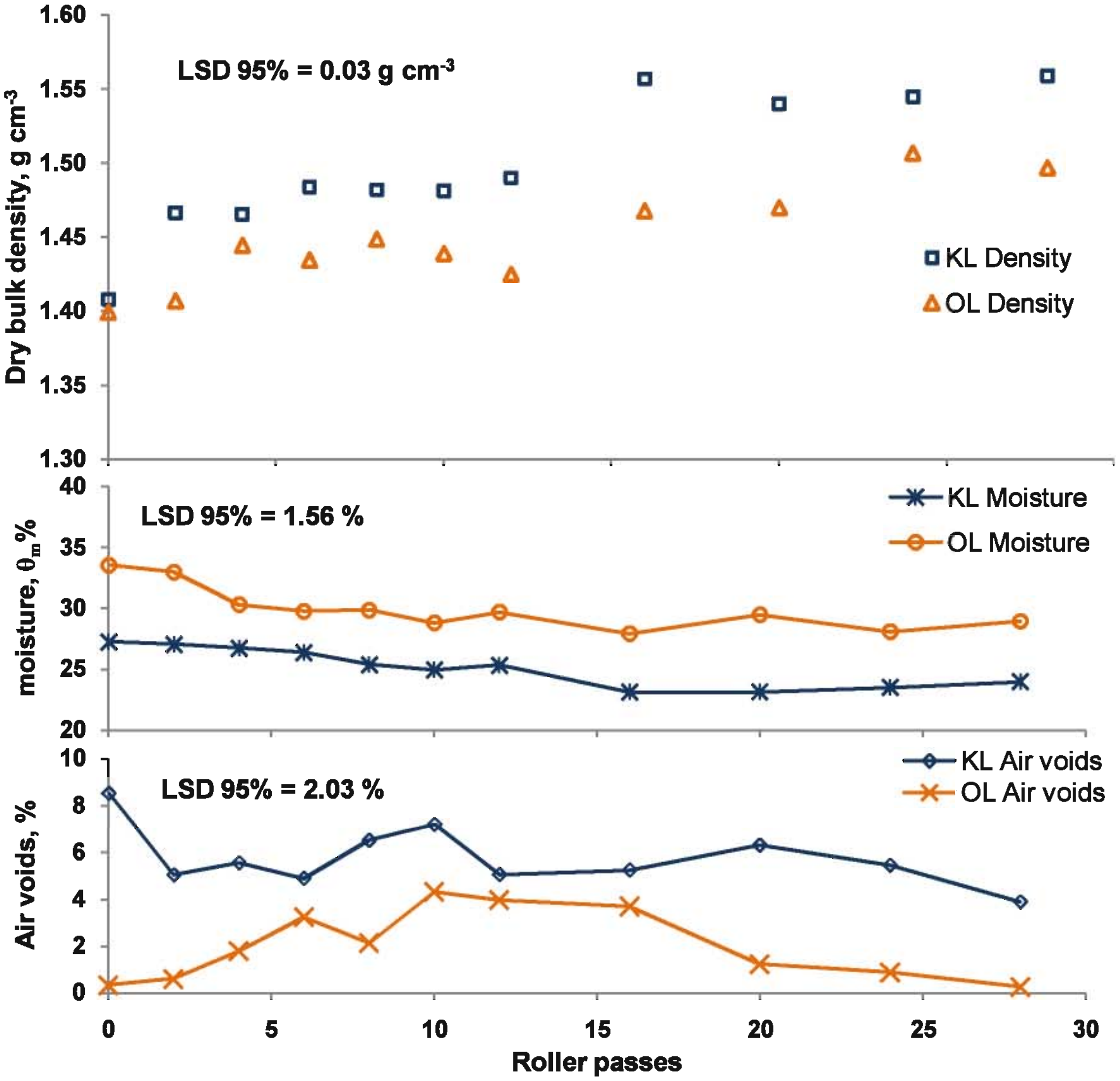

Figure 5.7 Experiment 2 'single session'. OL and KL soil depth 0-30 mm using a 920 kg m^{-1} roller (600 mm diameter). 28 roller passes over four days 24-27th April 2006. Significant increases in dry bulk density were determined for OL soil up to 24 roller passes and KL soil up to 15 roller passes.**

Results for KL soil indicated a significant** increase in the dry bulk density from an initial 1.41 g cm^{-3} to 1.56 g cm^{-3} after 16 roller passes with air voids constantly above 4%. OL soil indicated a significant** increase in dry bulk density from 1.40 g cm^{-3} to a maximum of 1.51 g cm^{-3} after 26 roller passes. Soil drying could have increased dry bulk density from shrinkage beyond 16 roller passes in the OL soil however air voids fell below 2% which would reduce the potential to for compaction.

In the depth 30-60 mm KL soil dry bulk density increased significantly* after two roller passes but no significant change in density was determined for OL soil (Figure 5.8).

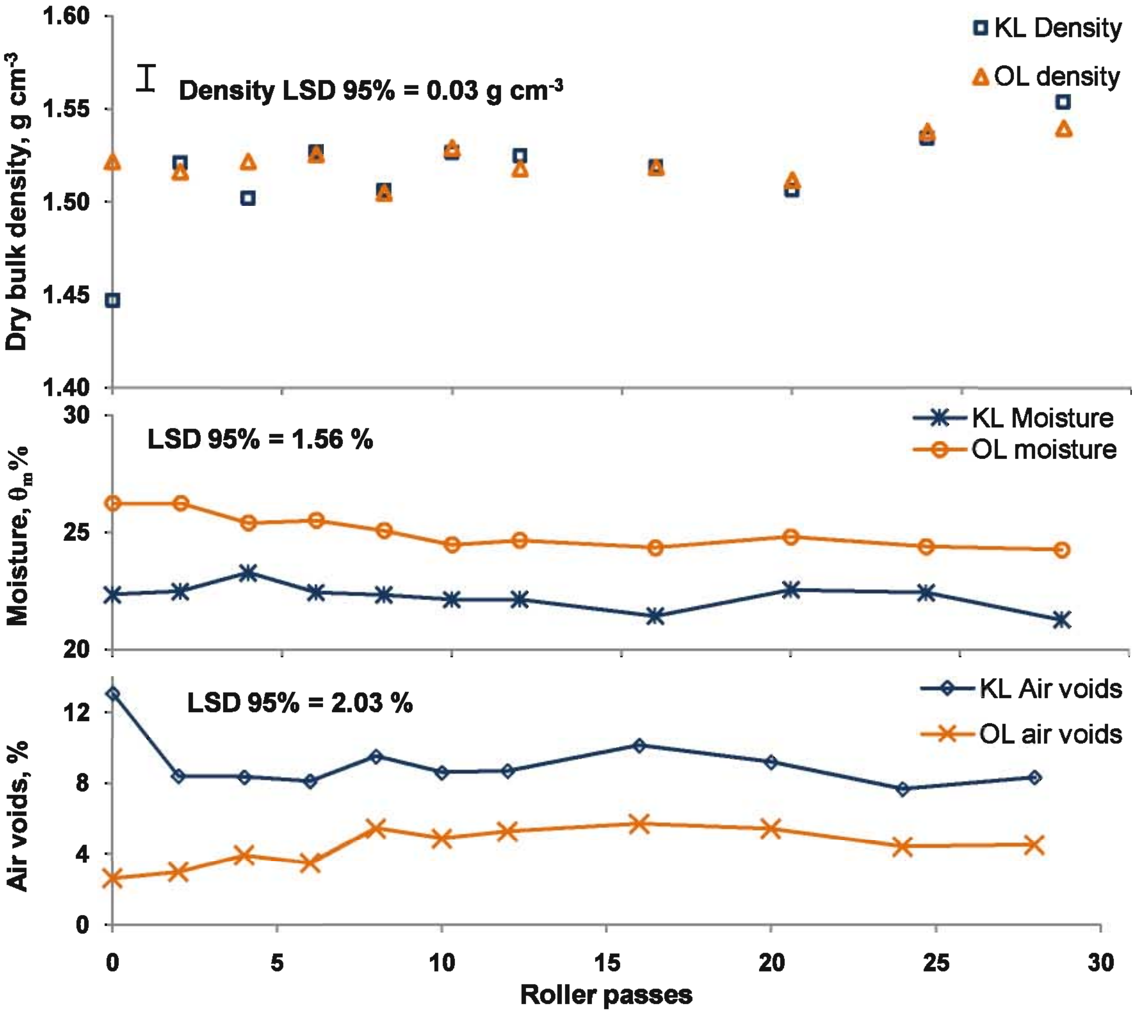

Figure 5.8 Experiment 2 'single session'. OL and KL soil 30-60 mm depth using a 920 kg m^{-1} roller (600 mm diameter). 26 roller passes over four days 24th- 27th April 2006. Air voids and gravimetric moisture content on the secondary y axis. Significant increases in dry bulk density were determined for KL soil up to two roller passes.**

Soil moisture declined at a slower rate than the 0-30 mm depth and therefore soil air voids remained relatively constant. Evaporation from the soil closest to the surface will be greater than for soil at greater depths and result in different moisture within the soil profile.

5.3.2.1 Maximum dry bulk density resulting from roller compactive force – Experiments 1 and 2

Experiments 1 and 2 indicated maximum dry bulk densities achieved from a roller in a specific soil physical condition. For the 0-30 mm depth these were 1.55 g cm^{-3} (725 kg m^{-1} roller) and 1.61 g cm^{-3} for the 920 kg m^{-1} roller. All rolling sessions demonstrated a sensitivity to soil moisture content and air voids. Rolling did not increase soil dry bulk density in either soil when air voids were below 2% regardless of soil density. Where air voids were great enough to allow for an increase in dry bulk density between two and six roller passes (two drum roller) were required for a specific soil physical condition.

Increase in dry bulk density in the 30-60 mm depth was to a maximum of 1.52 g cm^{-3} for KL soil however OL soil was already at this density and no further increase occurred. For the depth 60-90 mm a maximum dry bulk density of 1.45 g cm^{-3} occurred (725 kg m^{-1} roller). Changing to the heavier 920 kg m^{-1} had no effect on dry bulk density at these depths.

5.3.2.2 *Comparison of rolling management – Experiment 1 and 2*

Experiment 2 (single session) was undertaken at the same time as Session 5 of Experiment 1 (multiple sessions) which enabled a comparison of the two roller treatments at the end of April 2006 (Table 5.4):

Table 5.4 Experiments 1 (Session 5) and 2 April 24th- 27th 2006. Soil dry bulk density, moisture and air voids. LSD 95% for density = 0.028 g cm^{-3}. LSD 95% for moisture = 1.05%.

Soil	Experiment	Initial density(ρ_d)	Final density (ρ_d)	Initial moisture	End moisture	Initial air voids	End air voids
		g cm^{-3}	g cm^{-3}	%	%	%	%
OL	1	1.54	1.61	26.2	23.6	1.5	1.8
KL	1	1.57	1.59	24.8	22.8	1.8	3.8
OL	2	1.40	1.51	33.5	28.9	<1.0	<1.0
KL	2	1.41	1.56	27.2	23.9	8.4	3.9

Overall increase in dry bulk density (resulting from the compactive effect of the roller, the background shrinkage effect of drying and the shrinkage effect of roller-compaction-induced drying) was greater for the multiple session protocol for both soils. Initial moisture content was lower for the multiple session treatment indicating benefits of reduced gravimetric moisture content accruing from a multiple rolling session regime. Final dry bulk density for the single session OL soil was restricted due to high moisture and low air voids. Multiple rolling sessions is therefore more likely to produce a pitch profile with lower moisture content and a higher dry bulk density by the end of the spring rolling period, particularly in the higher clay OL soil.

5.3.3 Field Experiment 3 – Early summer rolling

Experiment 3 was a continuation of the spring rolling Experiment 2 but conducted in early summer 2006 when the soil moisture had reduced during the 46 days following Experiment 2. The experiment was conducted in two separate rolling sessions and the results are presented in Figure 5.9 and are added to the Experiment 2 results to demonstrate the effect of soil drying.

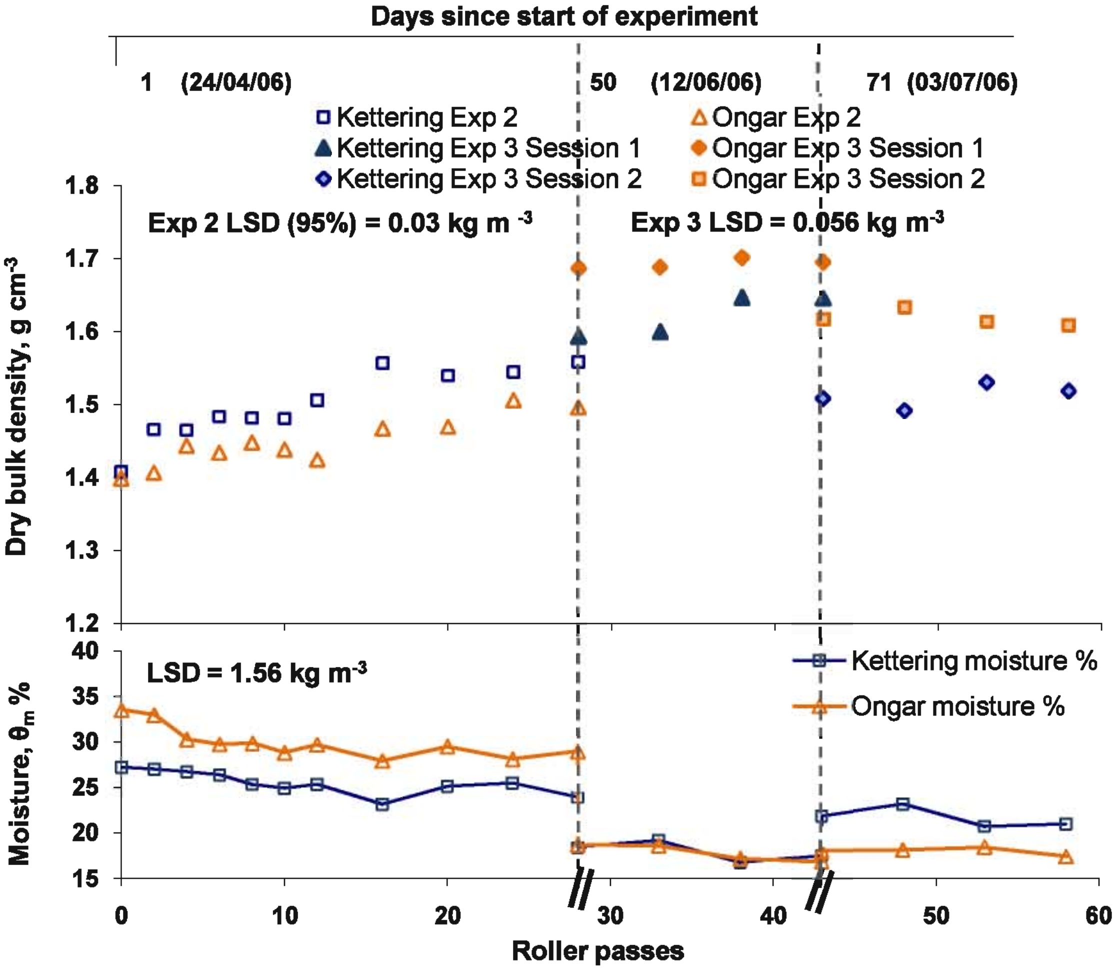

Figure 5.9 Dry bulk density and gravimetric moisture for Experiment 2 and 3, 920 kg m^{-1} roller (600 mm diameter) OL and KL soil. Breaks in time between roller sessions are denoted by ||. Note: The first data point for each session was measured before rolling. Significant* increase in KL soil dry bulk density was determined between 28 and 43 roller passes.

A significant* increase in soil dry bulk density occurred for the KL soil 1.59 to 1.66 g cm^{-3} however with soil drying (19%-17% gravimetric moisture content) this could have been, at least in part, due to soil shrinkage. No significant increase in dry bulk density occurred for OL soil.

Irrigation of the plots between sessions 1 and 2 increased moisture content before the second rolling session. All plots had the same water application (60 mm split over two days) but the lower starting moisture for Session 2 in OL soil moisture was either a result of the higher bulk density OL soil reducing infiltration and therefore resulting in water run-off or that the OL soil had dried to a lower level prior to irrigation. Moisture content was not measured before watering. Rolling 48 hours after irrigation resulted in no significant increase in dry bulk density for either soil. No significant changes in dry bulk density were determined for any other depth of soil for either of the roller sessions in Experiment 2 using the 920 kg m^{-1} roller.

5.3.3.1 Summary of Experiments 1, 2 and 3

The compactive potential of the 725 kg m^{-1} and 920 kg m^{-1} rollers under a range of soil moisture contents was determined and the maximum compactive potential achieved was 1.54 g cm^{-3} and 1.61 g cm^{-3} at 25% and 24% gravimetric moisture content for these two roller weights respectively. Rolling of soil above these maximums indicated no increase in dry bulk density at moisture contents ranging between 27% and 15% for KL soil and 34% to 16% for OL soil.

Soil drying resulted in soil shrinkage increasing soil dry bulk density and is relevant in terms of final pitch bulk densities. The shrinkage was more noticeable in the OL soil and this is discussed in more detail in Section 5.3.7. Rolling protocols increased final dry bulk density significantly** more than drying only control plots.

Soil air voids were consistently between zero and 5% throughout the spring rolling period for OL soil but generally were below 2% when soil moisture content was above 25% (Figure 5.10). The dry bulk densities of data points circled and labelled A in Figure 5.10 occurred after prolonged drying (Session 6) and were not achieved through rolling.

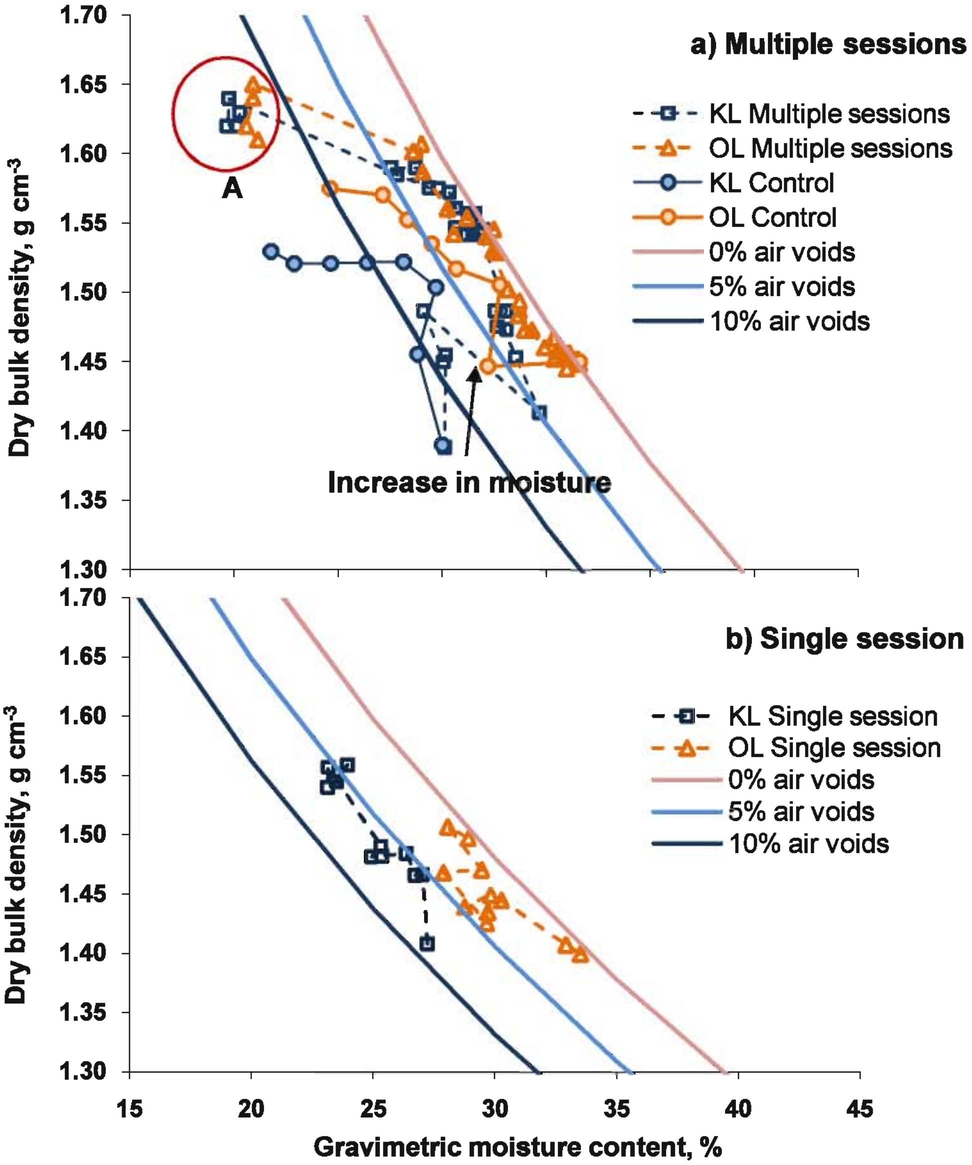

Figure 5.10 Experiment 2 and 3 dry bulk density and gravimetric moisture content relationship, Multiple sessions (a) and Single session (b). Soils maintained low air voids throughout early spring with a reduction in air voids only occurring in drier conditions during Experiment 3 circled (A) which occurred after soil drying and not as a result of rolling. Dashed lines indicate consecutive passes path.

Standard compaction test results in Section 4.2.2 determined the Proctor maximum dry bulk density to be 1.68 g cm^{-3}. Comparison with Experiment 1, 2 and 3 results indicate that 95% of the Proctor maximum density was achieved for OL soil and 92% for KL soil by rolling alone. Approximately 98% of Proctor maximum was achieved with further drying. Rolling in spring moisture conditions indicated that air voids were consistently between zero and 5% which was comparable to the laboratory compaction tests. Parson's (1992) indicated that approximately 90% of Proctor optimum was achievable with a roller of 1000 kg m^{-1} in a sandy clay soil. This is below the dry bulk density that was achieved in these rolling experiments but Parson's experiments was not considering an established soil profile incorporating grass roots. The target dry bulk density of 1.65-1.75 g cm^{-3} stated by Adams *et al* (2004) was shown to be achievable with rolling and additional drying.

Depth of compaction was to 60 mm and was 90% of Proctor maximum. This is in agreement with Parsons (1992) who determined that 90% of Proctor was achievable to a depth of 50 mm for a 500 kg m^{-1} roller. For a 1000 kg m^{-1} roller Parsons determined compaction at 90% of Proctor could be to 100 mm however the experimental plots in this study were at this density before rolling took place. If 90% of Proctor maximum dry bulk density is achievable using a 1000 kg $^{-1}$ roller, the expected achievable rolling dry bulk density for depths to 100 mm would be 1.51 g cm^{-3} at an optimum moisture content of 25%, assuming the accepted air void standard as 5% (Parsons, 1992; Department of transport, 2006).

5.3.4 Field Experiment 4 – Rolling speed in spring moisture conditions

Experiment 4 assessed the effect of roller speed on the compactive potential of the roller under different soil physical conditions during three separate rolling sessions in spring moisture conditions. Two roller speed treatments were compared: 0.7 km h^{-1} and 0.35 km h^{-1} both using a two drum roller (920 kg m^{-1}; 600 mm diameter).

The three roller sessions were divided with a 10 day break between Sessions 1 and 2 and a 15 day break between Sessions 2 and 3. Soil moisture declined between sessions 1 and 2 due to natural drying conditions and increased again between sessions 2 and 3 as a result of natural precipitation.

Results for both soils for the depth 0-30 mm are presented in Figure 5.11.

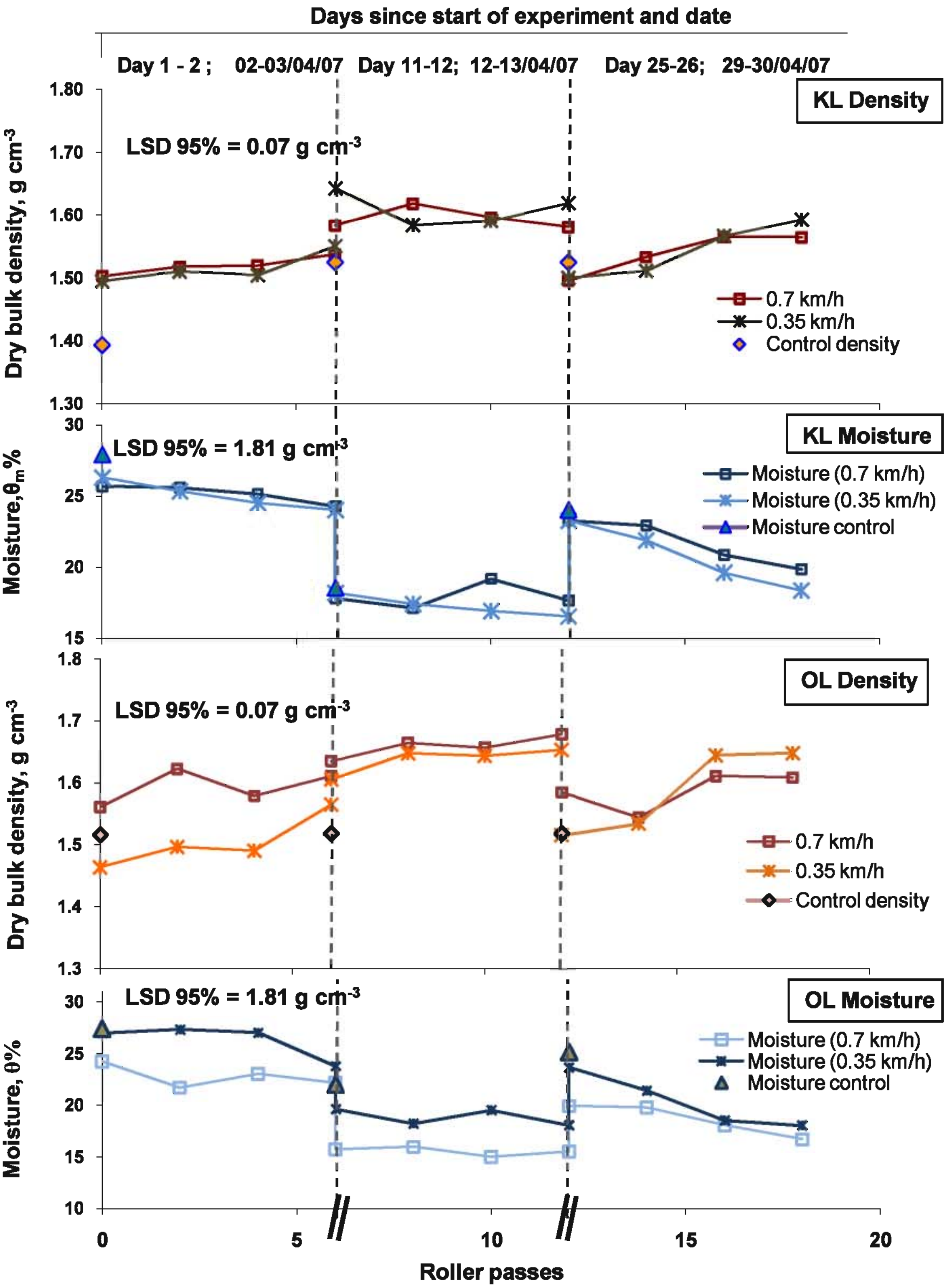

Figure 5.11 Experiment 4 dry bulk density and gravimetric moisture against roller passes for KL and OL soil. Two roller speed treatments were conducted with a 920 kg m^{-1}, 600 mm diameter roller. Three roller sessions are divided by breaks in time denoted by || and each roller session took two days to complete. Note: The first data point for each session was measured before rolling

No significant difference in roller compactive potential of the 920 kg m^{-1} roller was determined for the two roller speeds for the KL soil. Initial dry bulk density for OL soil was significantly* lower for the 0.35 km h^{-1} treatment and therefore the significantly* greater increase in dry bulk density for the 0.35 km h^{-1} roller compared to the 0.7 km h^{-1} in Session 1 cannot be attributed to the roller speed.

The compactive potential of the roller was no greater than 1.55 g cm^{-3} for the KL soil at a gravimetric moisture content of 24%. Changing moisture content affected OL results with the only increase in dry bulk density attributable to roller compactive force being 1.56 g cm^{-3} at 22% gravimetric moisture content. All other increases in dry bulk density for both soils were associated with changes in soil moisture content.

The relationship between spring rolling and soil air voids is plotted in Figure 5.12.

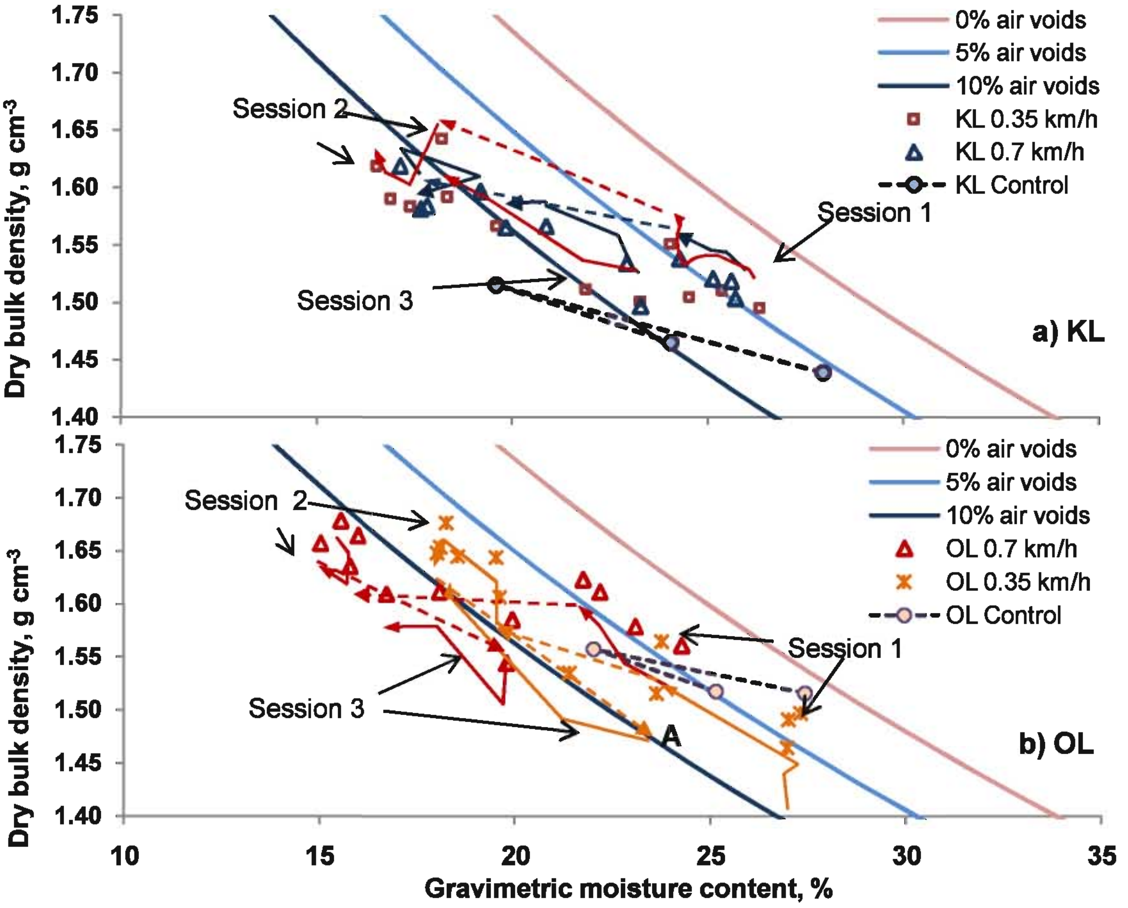

Figure 5.12 Experiment 4 indicating gravimetric moisture content and dry bulk density relationship for KL (a) and OL (b) soil. Two roller speed treatments were conducted with a 920 kg m^{-1}, 600 mm diameter roller. Dashed line indicates interval between rolling. Each roller session consists of four data points. Point A is the start of Session 3 after an increase in soil moisture content.

Re-wetting the soil after drying decreased the dry bulk density to a level that had previously been achieved at higher moisture content and drying of the soil increased bulk density at a slower rate than the reduction in bulk density resulting from an increase in moisture. This contrasts with the statement by Horn *et al* (1994) suggesting that dry bulk density increases with wetting and dying cycles. As this soil is close to the surface this could be a result of soil swelling due to rainfall/irrigation followed by drying with a reduced shrinkage due to low overburden stress. Therefore rolling after rainfall is required to reinstate dry bulk density as the soil dries as density will not be completely regained from soil shrinking alone.

5.3.4.1 Summary of Experiment 4

Comparison between roller speeds of 0.7 km h^{-1} and 0.35 km h^{-1} determined no significant difference between roller speed on final soil densities for both soils in spring rolling conditions. Final densities were influenced by rolling and soil moisture content.

Maximum compactive dry bulk density achieved by rolling for the OL soil was 1.56 g cm^{-3} and for the KL soil it was 1.55 g cm^{-3}. These were achieved with 4 to 6 roller passes. Dry bulk densities above these figures were accompanied by a reduction in soil moisture content and therefore cannot be attributed to roller compactive force.

A significant* difference in dry bulk density occurred between unrolled control plots and experiment rolling treatments for both soils after soil drying between Session 1 and 2. This was largely as a result of a greater reduction in soil moisture from the rolled plots. This also occurred in Experiment 1 and confirms potential benefits from early spring rolling in reducing soil moisture either by reduced infiltration rates or increases in bulk density lowering soil porosity.

5.3.5 Field Experiment 5 – Summer pitch drying and rolling

The survey of current rolling practice ascertained a wide diversity in pre-match rolling techniques due to reasons ranging from labour and equipment availability and differing climatic conditions to cricketing aspirations (i.e. desired pitch quality) and different ideas of what best practice might be. Experimental rolling treatments were designed to determine timing of rolling in the summer after irrigation in the period before a match and to assess the drying process. Results are presented in Figure 5.13.

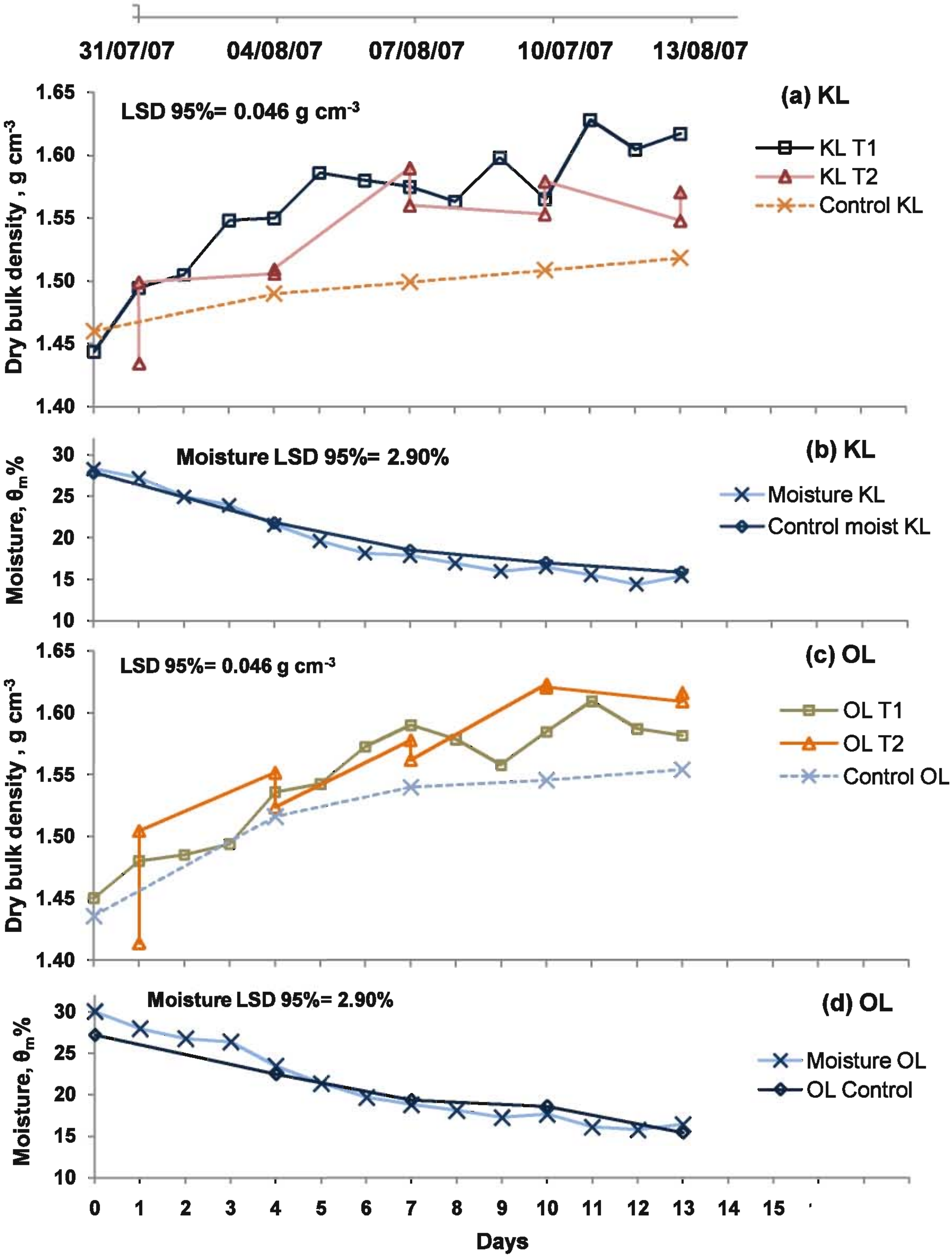

Figure 5.13 Dry bulk density and moisture change over time during 13 days of drying in Experiment 5 for KL, (a) and (b), and OL, (c) and (d) at 0-30 mm depth. The two roller treatments were T1- daily rolling (four passes on the first day followed by two passes per day), T2 – reduced rolling (6 passes at 3 day intervals). Significant* differences in bulk density between treatments were determined but these were not consistent. Density data points for T1 measured after rolling daily. Data points for T2 measurements taken on day of rolling, before and after rolling.

Plots used for the experiment had been rolled in the spring rolling Experiment 3 and had a range of starting dry bulk densities. During the experimental period the daily temperature mean was 16°C (daytime mean 21°C; night mean 11°C) and one day of light rain occurred during the experiment necessitating temporary covering of the plots.

Rolling was first undertaken 12-18 hours after irrigation of the plots which resulted in significant** increases in dry bulk density for both KL Treatments and one of the OL treatments for depth 0-30 mm. Further significant** increases were determined for Treatment 1 (Daily rolling of two passes) but these were not completely attributable to rolling due to a reduction in soil moisture content. No further statistically significant increases in dry bulk density were determined for either soil for Treatment 2 (Reduced rolling; six passes every 3 days) in the 0-30 mm depth. Other points of note:

- Dry bulk density on the rolled plots was significantly** greater than on the unrolled control plots after five days of drying.
- Final dry bulk densities for Treatment 1 (daily rolling) were 1.61 g cm^{-3} and 1.58 g cm^{-3} for KL and OL soil respectively and 1.57 g cm^{-3} and 1.61 g cm^{-3} for KL and OL respectively in Treatment 2 (3 day rolling). The difference between these densities was not statistically significant although they were all significantly** higher than their initial dry bulk densities and the control plot final densities.
- No significant differences in dry bulk density were determined for depth 30-60 mm however a significant** increase from six roller passes was determined for KL soil at depth 60-90 mm which increased from a dry bulk density of 1.46 g cm^{-3} to 1.51 g cm^{-3}, but not in the OL soil, and with no further significant increase for the duration of the experiment.
- No significant increase in dry bulk density occurred at depths below 90 mm.
- Moisture content declined significantly** during the experiment however this was only significant for the three depths 0-30 mm, 30-60 mm and 60-90 mm. Final moistures after 14 days drying were not significantly different.

A closer analysis of Treatment 2 (reduced rolling) confirmed the lack of increase in dry bulk density from roller compactive force after the first rolling session. Data measurements were taken before and after six roller passes on the same day with minimal change in soil moisture content. Significant** increases only occurred in the 0-30 mm depth and only after the first six passes for both soils. Dry bulk density was increased with the first rolling session with a 920 kg m^{-1} roller to a maximum of 1.50 g cm^{-3} for KL soil and 1.51 g cm^{-3} for OL soil at a moisture content of 27% and 28% respectively. After the initial increase from rolling in day one any further increases in bulk density were influenced by the reduction in soil moisture content.

Figure 5.14 shows the relationship between gravimetric moisture content and dry bulk density for depths 0-30 mm for both treatments.

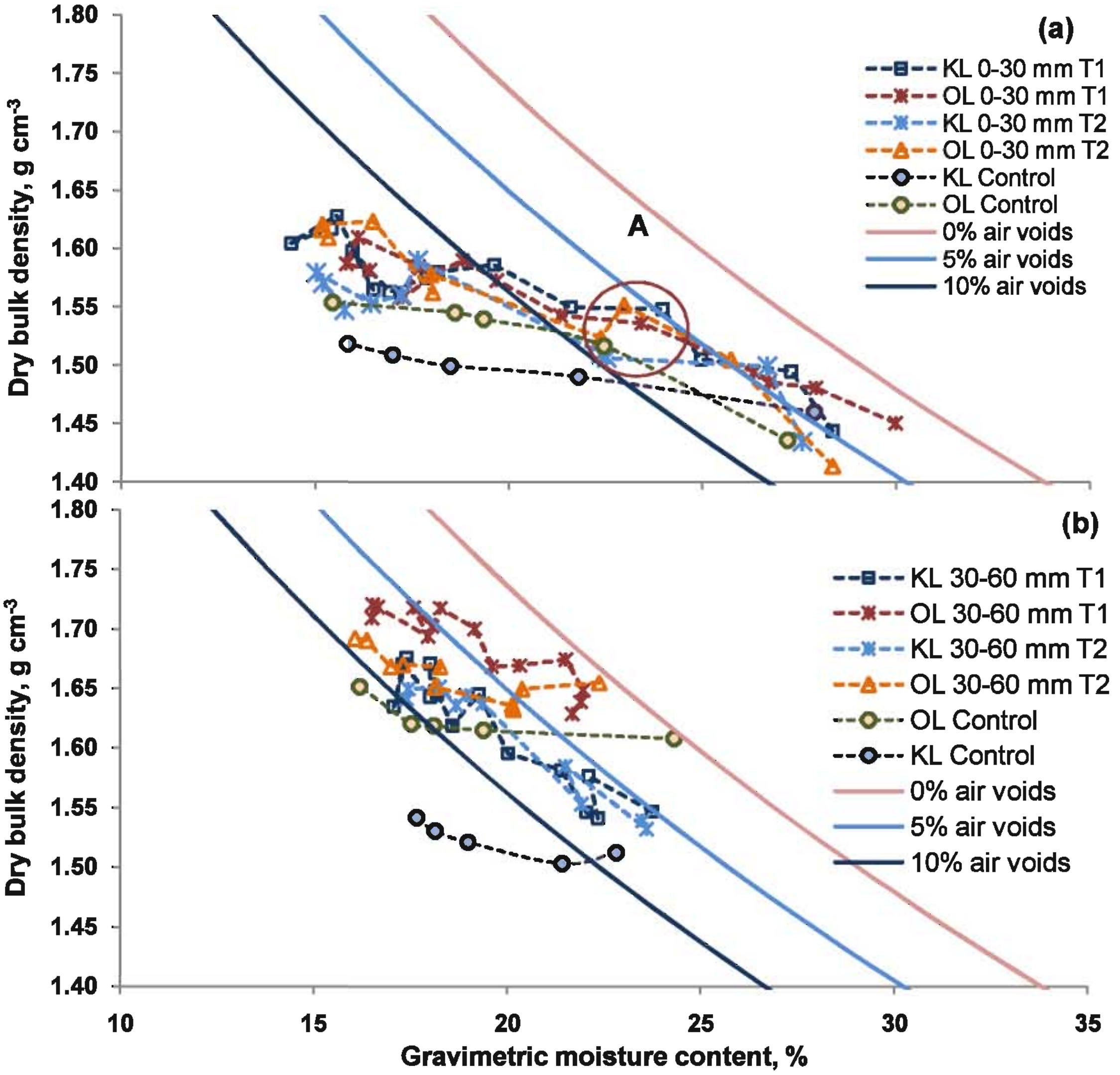

Figure 5.14 Gravimetric moisture content and dry bulk density relationship during Experiment 5 for KL and OL soil, 0-30 mm depth (a) and 30-60 mm (b). Data points circled (A) indicated no increase in dry bulk density after 10 roller passes for Treatment 1 (daily rolling) and 6 roller passes for Treatment 2 (3 day rolling) for the depth 0-30 mm. No significant increase in dry bulk density resulting from rolling was determined for depth 30-60 mm.

The circled (A) data points in Figure 5.14 are after 3 days (KL T1) and 4 days (KL 2 and OL 1 and 2) having received 8-10 roller passes (daily rolling) or 6 roller passes (reduced rolling). The next rolling session did not increase the dry bulk density for any treatment. It is therefore likely that further increases in dry bulk density for the duration of the experiment were largely due to the drying of the soil and it was therefore not possible to determine further increases in density from the rollers compactive force.

Compared to the 0-30 mm depth the 30-60 mm depth had lower initial moisture content and dried at a slower rate. No significant increases in dry bulk density were determined when rolling occurred and gradual increases in dry bulk density are likely to be a result of soil drying.

5.3.5.1 Soil moisture

Soil moisture declined at all depths during the 14 day experiment and this was analysed for all of the 20 trial plots. Initial dry bulk densities ranged from 1.25 g cm^{-3} to 1.45 g cm^{-3} for the 0-30 mm depth and 1.37 g cm^{-3} to 1.65 g cm^{-3} for depth 30-60 mm and for the depths 60-90 mm, 90-120 mm and 120-150 mm the dry bulk density ranged between 1.51 g cm^{-3} and 1.61 g cm^{-3}. Gravimetric and volumetric moisture content for all plots during the experiment are plotted in Figure 5.15.

Table 5.5 Daily weather conditions and temperatures (°C), two colour gradient representing the value in the cell. S = sun, C = cloud and R = rain. To be read in conjunction with Figure 5.15.

Average daytime conditions	S	C/R	S	S	S	S	S	S	S	S	S	S	S
Day temp max	20	17	22	25	27	22	20	22	19	23	25	18	20
Night temp min	12	11	13	14	17	9	10	9	7	10	13	11	13
Mean	16	14	18	20	22	16	15	16	13	17	19	15	17

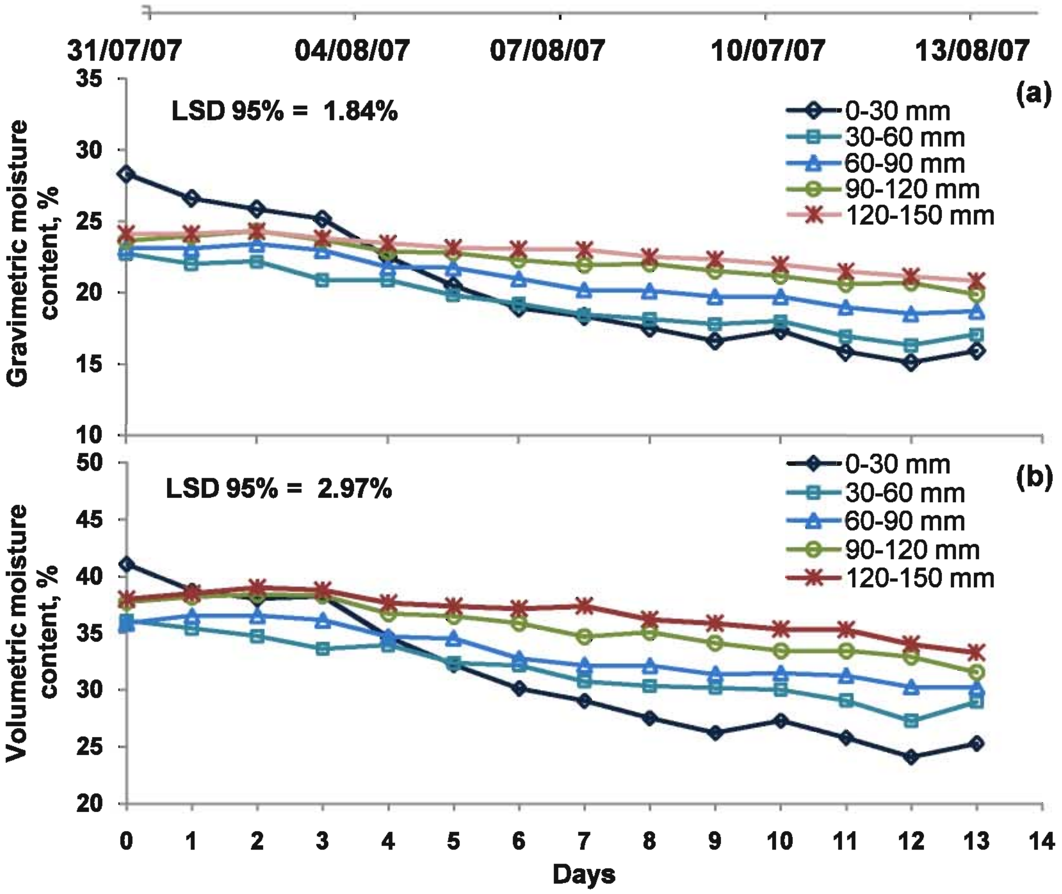

Figure 5.15 Gravimetric (a) and Volumetric (b) moisture content for all depths and all trial plots (both soils) Experiment 5 2007.

Moisture content at all depths declined significantly** during the experiment and there were significant** differences between depths. The shallower the soil depth the greater was the decline in moisture. This is due to rootmass distribution in the profile and evaporation being greater closer to the soil surface. This was particularly noticeable for the 0-30 mm depth which declined from 28% to 16%. Soil moisture content differences are to a certain extent a reflection of soil bulk density which is illustrated by determining volumetric moisture content that takes into account soil bulk density (Figure 5.15b). The same pattern of drying occurs for volumetric moisture content although the differences in the first four days of drying are reduced between the 0-30 mm depth and the other depths. This is due to the relatively low dry bulk density of the 0-30 mm depth after saturation. The drying pattern was the same for both soils but there were statistical differences between soils which are discussed in more detail in Section 5.4.2.

Irrigation of the experimental plots was carried out over two days. The moisture differential suggests that even wetting through the whole profile is difficult to achieve particularly as soil expands at different rates within the profile due to differing overburden stress. Saturation moisture content will depend on soil porosity as a result of the soil bulk density and soil hydraulic conductivity will vary across the soil profile with changes in dry bulk density.

In practice, this differential in moisture content between depths is particularly relevant to cricket pitch rolling and in particular the difference between 0-30 mm and 30-60 mm. Rolling compaction efficiency has previously been determined to be dependent on soil moisture but with the 0-60 mm depth having a range in moisture content a compromise needs to be considered. Dry bulk density in the 0-30 mm depth is reduced substantially by saturation and subsequent expansion but considerably less so for the 30-60 mm depth. Compaction of the 0-30 mm depth is therefore more crucial in pitch preparation after irrigation; however it has been shown that with 10-12 roller passes of a 920 kg m^{-1} roller, densities as high as the compactive potential of that roller weight, can be achieved in the 0-30 mm depth.

Having determined differences between depths using mean data it is important to note that differences between plots were significant** in terms of dry bulk density and gravimetric moisture content. Plots with a high initial dry bulk density had lower moisture content compared to plots with a low initial dry bulk density. Comparison of two extremes of plot initial dry bulk density illustrates this, a high and a low initial density. Both of the plots were rolled in the daily rolling treatment for Experiment 5. The low density plot had received no spring rolling and the high density plot had previously received 18 roller passes in the spring rolling Experiment 4 (920 kg m^{-1} roller; 600 mm diameter; 0.7 km h^{-1}) (Figure 5.16 and 5.17).

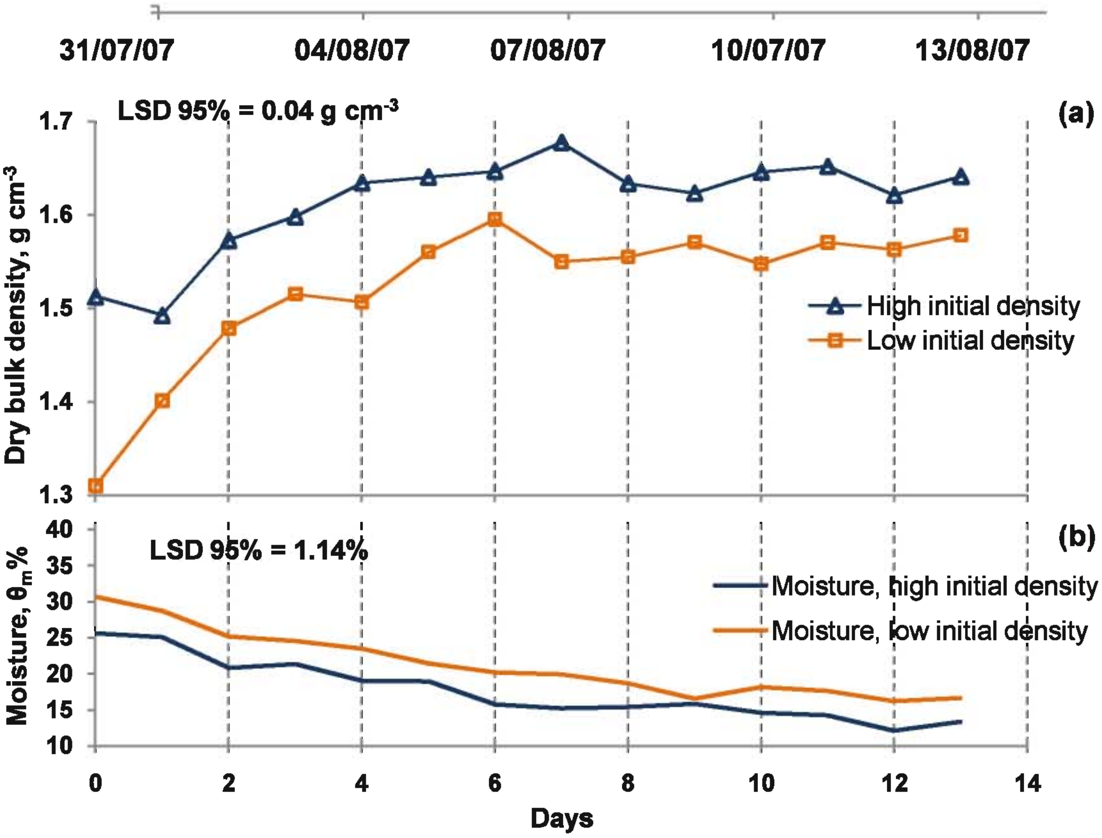

Figure 5.16 Dry bulk density (a) and gravimetric moisture content (b) on OL soil, high and low initial density plots during Experiment 5. Significant differences occurred between plots for moisture and dry bulk density through much of the experiment.**

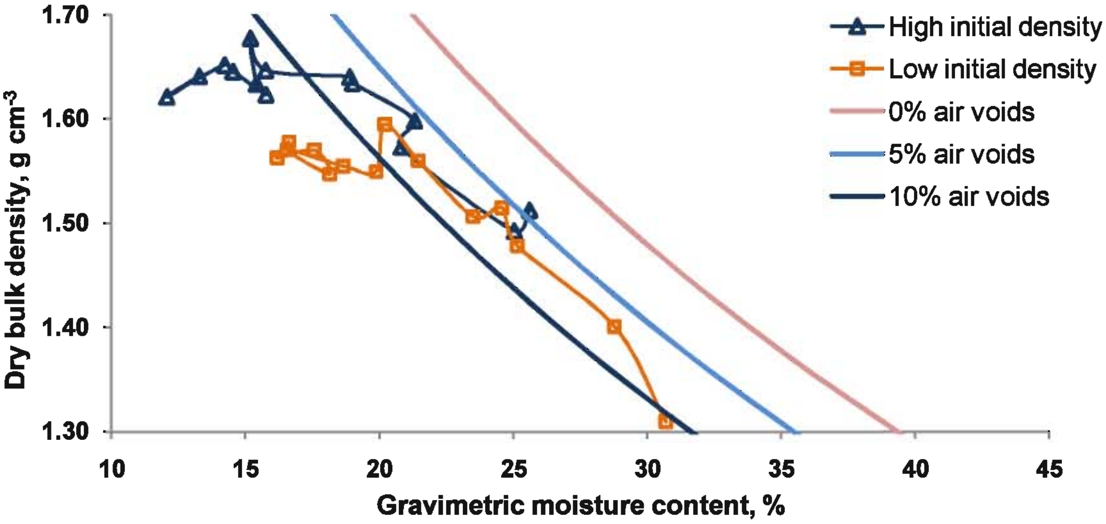

Figure 5.17 Gravimetric moisture and dry bulk density relationship during Experiment 5 for a high and a low initial density plot. Air voids were not significantly different between the two plots for much of the experiment however the final densities of the high start density were greater than the low start density, largely due to differences in moisture content.

Higher void ratio in lower density soils leads to a higher initial level of gravimetric moisture content although air voids within the two different bulk density soils and volumetric moisture levels are similar.

With low gravitational drainage rates, particularly if the underlying soil is at a higher bulk density, the mass of moisture remaining in the soil is greater for the low bulk density soil and although drying was determined to be faster in the lower bulk density soils the final moisture content was greater than the soil with the higher initial dry bulk density. Low dry bulk density pitches i.e. new or re-laid pitches or those having been mechanically decompacted, that are not rolled in the spring could result in higher moisture levels at the start of the playing season which could have consequences for pitch playability.

5.3.5.2 Summary of Experiment 5

Experiment 4 sought to examine pre-match cricket pitch rolling in summer climatic conditions following irrigation using a 920 kg m^{-1} two drum (600 mm diameter) roller. The only significant** increases in dry bulk density in the 0-30 mm depth resulting from rolling were achieved after the first rolling session and this was for three of the four treatments. This was after four to six roller passes depending on treatment. The treatment that did not increase dry bulk density significantly was on OL soil that had higher initial moisture and 2% air voids. No significant differences were determined for depth 30-60 mm or below 90 mm however a significant** increase from six roller passes was determined for KL soil at depth 60-90 mm.

Final densities for all treatments were significantly** different from their respective start densities but not statistically different from each other. For Treatment 1 (daily rolling) final densities were 1.61 g cm^{-3} and 1.58 g cm^{-3} for KL and OL soil respectively and 1.57 g cm^{-3} and 1.61 g cm^{-3} for KL and OL soil respectively in Treatment 2 reduced rolling) for the 0-30 mm depth. All treatments had densities greater than unrolled control plots after the initial rolling session but this was not consistently significant until six days after the start of rolling.

Initial rolling of four and six passes increased densities to between 1.48 g cm^{-3} and 1.50 g cm^{-3} for all treatments. Further rolling at this stage may have achieved higher densities that have previously been shown to be achievable by this roller weight in similar soil moisture conditions. Soil drying throughout the experiment meant that increases in dry bulk density could not wholly be attributed to rolling. However after 8-10 roller passes of every day rolling and six roller passes of three day interval rolling, no gains in dry bulk density could be attributed to rolling. The dry bulk density at this point ranged from 1.51 g cm^{-3} to 1.55 g cm^{-3} for all the treatments and this difference was not statistically significant.

Moisture content declined significantly** for all plots during the experiment. Final moistures after 14 days drying were not significantly different in the 0-30 mm depth. The shallower the soil depth the greater was the decline in moisture. This was particularly noticeable for the 0-30 mm depth which declined from 28% to 16%.

Initial moisture contents at this time (August 2007) were shown to be influenced by dry bulk density. Higher bulk density soils had lower gravimetric moisture content after irrigation and maintained lower moisture content throughout the experimental period when compared to a low initial soil bulk density. Higher bulk density soils will reduce infiltration rates and take longer to reach saturation but will also have a lower porosity reducing maximum moisture content. Soil with a higher initial bulk density maintained a higher level of dry bulk density regardless of rolling treatment due to the consistently lower moisture content.

Not rolling low bulk density pitches pre-season in the spring could result in higher moisture levels at the start of the playing season due to rainfall or irrigation close to a match particularly in high clay cricket loams. Although pre-match rolling can increase bulk density in the same way as spring rolling the potentially higher moisture contents resulting from no previous rolling will require a longer drying period to achieve the same level of pitch playability. This does not necessarily mean rolling in the spring but it appears that pitch preparation and drying would need to start earlier than 14 days before a match.

Reductions in bulk density as a result of irrigation were more pronounced in the 0-30 mm depth indicating greater expansion in the soil closest to the pitch surface. The resultant increase in soil voids leads to a higher initial moisture content before drainage. Slow drainage through the soil profile below will result in high soil moisture in the 0-30 mm depth requiring drying from evapotranspiration. Compaction by rolling of this depth is relatively efficient with a 920 kg m^{-1} roller and providing enough time has been allowed for pore drainage, soil air voids should be high enough to maximise the rollers compactive potential with up to 10 roller passes.

Rolling was undertaken after 18 hours but under similar drying conditions this could have been left for a further 48 hours. This would have allowed for the 0-30 mm depth to have had a reduced differential from the 30-60 mm depth due to drainage and evapotranspiration. This may also reduce roller sinkage which would decrease the roller compactive potential and possibly cause pitch damage. However if the plots had been allowed to dry to a point where soil moisture in the 0-30 mm depth was the same as the 30-60 mm depth this would have taken approximately five days. At this point soil moisture content would have been at approximately 20% which may be below the optimum moisture content for a roller of this weight. Maximum roller compactive dry bulk densities achieved with this roller in all experiments for OL soil were 1.61 g cm^{-3} which equates to an optimum gravimetric moisture content (assuming 5% air voids) of approximately 22% and for KL soil the maximum roller compactive dry bulk density of 1.55 g cm^{-3} would indicate an optimum gravimetric moisture content of 24%.

No significant differences were determined between the two rolling strategies. After a maximum of 10 roller passes no increase in dry bulk density from the roller compactive force occurred although further increases in dry bulk density occurred as a result of soil shrinkage resulting from a reduction in soil moisture content. Further rolling before a match will need to be justified for reasons other than increasing the pitch profile soil bulk density such as pitch playability concerning grass leaf condition.

5.3.6 Over winter changes in density

The initial dry bulk density for spring rolling will vary considerably between cricket venues and it will depend on a number of factors. As has already been mentioned new or re-laid pitches or those that have received some effective mechanical decompaction will be at a lower dry bulk density in the spring than pitches that have just received basic reseeding, scarification and light aeration. However winter climatic and biotic influences could also result in a change in soil bulk density through clay soil shrink/swell characteristics, frost heave or faunal activity.

Dry bulk density and moisture content data were recorded from eight plots with samples taken in September and March for two consecutive years 2006/2007 and 2007/2008 (Figure 5.18).

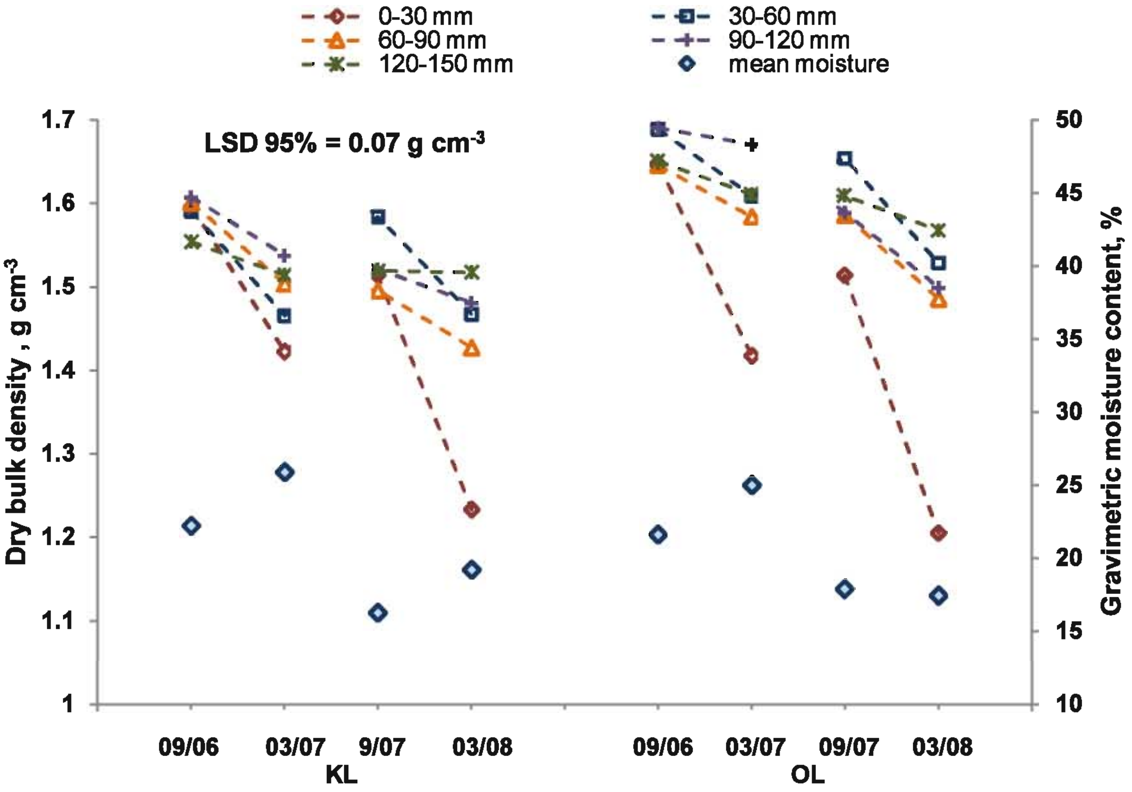

Figure 5.18 Change in dry bulk density over two winters 2006/07 and 2007/08 KL (left) and OL (right) soil. Mean moisture content for all depths indicated on the secondary y axis. Dashed lines link data points of the same depth for each winter period.

Dry bulk density in depths 0-30 mm, 30-60 mm and 60-90 mm all declined significantly** for both winter periods for both soils. Depth 90-120 mm declined significantly** for OL soil in the period 2007/08 but not for any other soil x period combination. No significant change in density was determined for depth 120-150 mm.

Differences between soils were significant* however the OL soil had higher initial autumn dry bulk density than KL soil. OL soil which has a higher level of expansive clay content had a significantly greater decline in dry bulk density in the 0-30 mm depth for 2006/07 winters compared to KL soil. Significant differences between soil types at other depths were not consistent. Soil moisture content increased for both measurements for KL soil and for the winter 2006/07 for OL soil by approximately 3% and is likely to account for some of the increase in dry bulk density. Higher moisture levels and duration of moisture levels are likely to influence the amount of swelling of the soil.

The decline in dry bulk density reduces with soil depth and differences between winter periods suggest the winter climatic conditions will affect this in different ways from one year to the next (Table 5.6).

Table 5.6 Decline in dry bulk density over the winter period September to March 2006/07 and 2007/08. Percent decline in density from autumn density in brackets. Shading indicates significant* decline.

Depth	0-30 mm	30-60 mm	60-90 mm	90-120 mm	120-150 mm
Soil / Date	g cm^{-3} (%)	g cm^{-3} (%)	g cm^{-3} (%)	g cm^{-3} (%)	g cm^{-3} (%)
KL					
06/07	0.17 (12)	0.13 (9)	0.10(6)	0.07 (5)	0.04 (2)
07/08	0.28 (23)	0.12(8)	0.07 (5)	0.04 (3)	0.00 (0)
OL					
06/07	0.25 (18)	0.08 (5)	0.06 (4)	0.02 (1)	0.04 (2)
07/08	0.31 (26)	0.13 (8)	0.10 (7)	0.09 (6)	0.04 (3)

Larger reductions in dry bulk density in the 2007/2008 winter, particularly for the 0-30 mm depth, are likely to be due to the high rainfall prior to sampling in late March. Cumulative winter rainfall for the two winters from September to April was not significantly different however March and April 2008 considerably higher rainfall occurred immediately preceding the sampling which would explain the low dry bulk density (Figure 5.19).

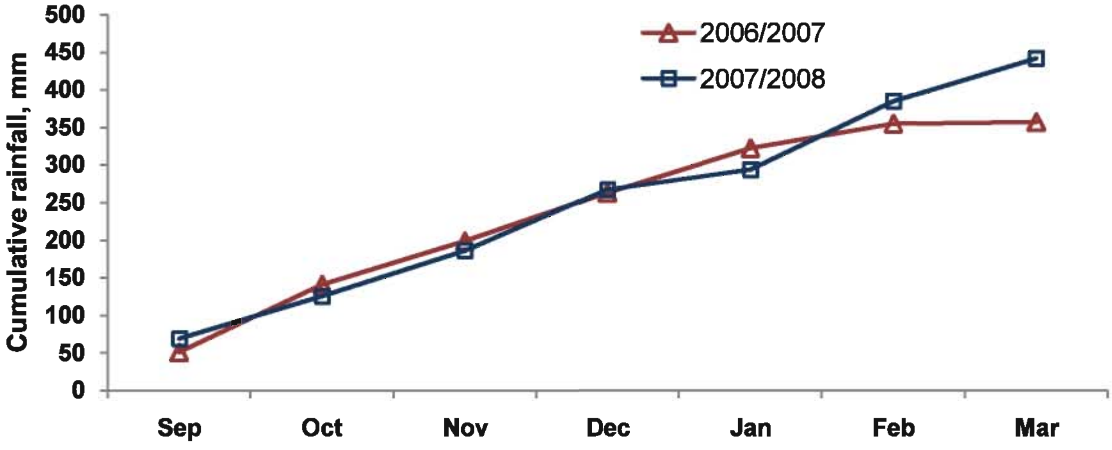

Figure 5.19 Cumulative precipitation for Silsoe for the two experimental winter periods (Silsoe weather station data).

Large reductions in bulk density in depth 0-30 mm are likely to lead to an increase in moisture content in the spring in this depth if the soil below is at a higher bulk density, restricting drainage as seen in the section above. It would therefore seem appropriate to recommend spring rolling on the basis of the need to increase the bulk density of this 0-30 mm depth to reduce moisture holding capacity. However further rainfall after rolling at any time in the spring or summer is likely to reduce bulk density again.

It was not determined how much of the bulk density reduction is recoverable from drying alone but experiments have indicated that depths below 90 mm are unaffected by the 920 kg m^{-1} roller and it is therefore likely that swelling at these depths is recoverable by drying and overburden stress. Closer to the surface soil swelling may not be fully recoverable by drying because of much larger expansion when swelling through the true surface compared to other depths.

5.3.7 Shrink swell characteristics

Shrink swell characteristics of the two soils were analysed with data recorded from the experimental plots during Experiments 1-4 using plots of different dry bulk densities at 0-30 mm depth. These measurements were taken for dry bulk density changes when no rolling took place and drying or shrinkage occurred. The initial density was a result of previous management since the plots were constructed in May 2006. A significant** relationship was determined, using regression analysis, for change in dry bulk density resulting from a change in gravimetric moisture content (Figure 5.20; Table 5.7).

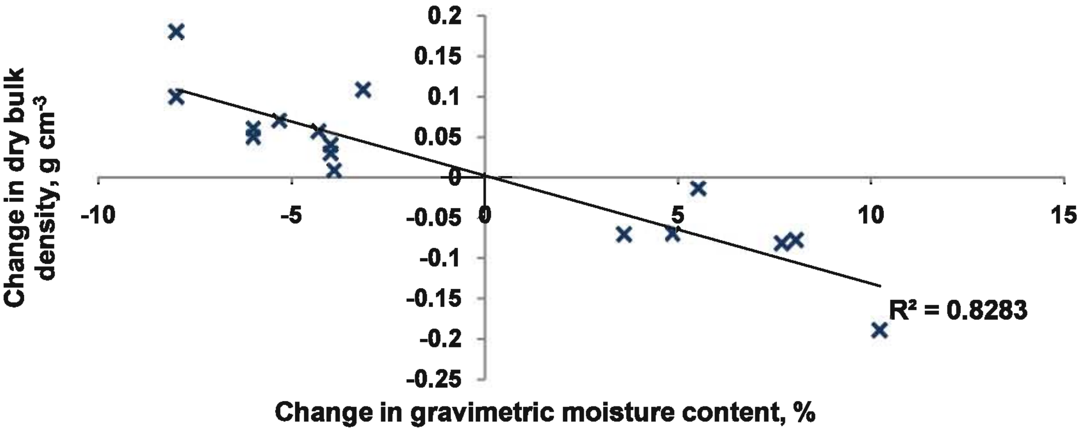

Figure 5.20 Relationship of change in dry bulk density against change in gravimetric moisture content for OL and KL soils; e.g. 10% increase in gravimetric moisture content results in a decline in dry bulk density of 0.132 g cm^{-3}.

Table 5.7 Regression model for shrink / swell characteristics of OL and KL soil (change in dry bulk density, g cm^{-3}). Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variable	Beta	Regression coefficient	p value
Intercept	-	0.001754	0.863
Moisture	0.910	-0.013372	<0.001
Summary Statistics			
Multiple R	0.910		
Multiple R^2	0.828		
Adjusted R^2	0.816		
F(1,14)	67.54		
p value	<0.001		

The model explains 82% of the relationship however other factors that did not make a significant contribution to the model were:

- Initial dry bulk density before the increase in moisture content and soil type. The initial bulk density was not significant for the range of densities measured (1.36 g cm^{-3} to 1.78 g cm^{-3}) although it would have been expected to be a factor in the amount of swelling.
- No statistically significant difference was determined between the two soils for change in dry bulk density resulting from a change in gravimetric moisture content. Shrink swell characteristics would have been expected to be greater in the higher clay OL soil however a high deviation and low degrees of freedom increased the LSD to a non significant level.

Examples of the affect of an increase in soil moisture on the soil dry bulk density in a cricket pitch context using the regression model are presented in Table 5.8.

Table 5.8 Example of reduction in dry bulk density resulting from an increase in soil gravimetric moisture content based on regression analysis in Table 5.7.

Increase in moisture, %	Reduction in density, g cm^{-3}
2	-0.025
4	-0.052
6	-0.078
8	-0.105
10	-0.132

The range within the confidence limits reflects the factors that are not significant in the model, initial dry bulk density and soil type, and therefore reduces its usefulness. However this provides an initial guideline of changes in density resulting from moisture increases, with a mean increase in dry bulk density of 0.0125 g cm^{-3} for a 1% increase in moisture content. It is likely that the number would be higher for high dry bulk density OL soil and lower for low dry bulk density KL soil. More experimental work needs to be done on this aspect of pitch bulk density change.

5.3.8 Playability measurements

Current standards for assessing playability has been established as hardness measured by a Clegg hammer and ball rebound from a 3 m drop height (Adams *et al*, 2004). These parameters were assessed from data derived from all of the experiments undertaken on the trial plots. Surface evenness and cracking were also assessed in Experiment 1 and 4 respectively.

5.3.8.1 Clegg hammer

Surface hardness of a soil with a specific texture type is dependent on the soil moisture content and dry bulk density. Clegg hammer (0.5 kg dropped from a height of 0.55 m) correlation with moisture alone was high within the range of densities measured (1.42 g cm^{-3} to 1.78 g cm^{-3}) (Figure 5.21).

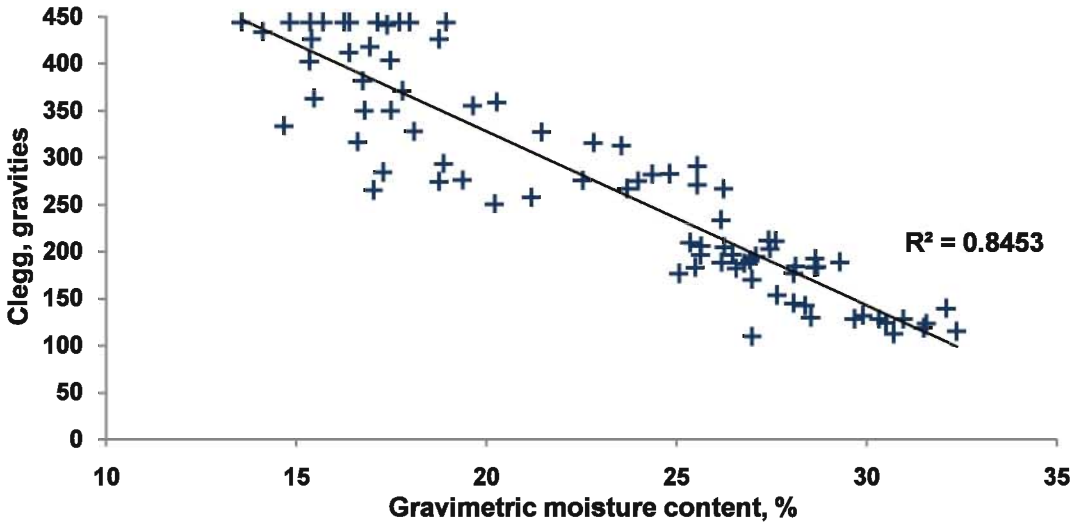

Figure 5.21 Clegg hammer (0.5 kg hammer; 0.55 m drop height) against gravimetric moisture content for soil depth 0-60 mm for KL and OL soils. Experimental trial plots 2006/2007.

Multiple regression analysis with dry bulk density and gravimetric moisture as explanatory variables produced a significant** model for the prediction of gravities measured by the Clegg hammer (Tables 5.9).

Table 5.9 Multiple regression model for all Clegg hammer measurements (G). Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variables	Beta	Regression coefficient	p value
Intercept	-	98.43	<0.001
Density	0.191	366.97	<0.001
Moisture	-0.833	-16.75	<0.001
Summary statistics			
Multiple R	0.935		
Multiple R^2	0.874		
Adjusted R^2	0.871		
F(2,81)	281.28		
p value	<0.001		

Adams *et al* (2004) suggest target dry bulk density of 1.65 g cm^{-3} to 1.75 g cm^{-3} and soil gravimetric moisture content targets of 18% to 20%. Using the model coefficients in Table 5.9, these targets would be achieved between 369 and 406 g (0.5 kg hammer; drop height 0.55 m) (Table 5.10). Recommended Clegg hammer gravities of 360 g (Adams *et al*, 2004) are based on a Clegg hammer using a 2.25 kg hammer dropped from 0.45 m and therefore bear no relation to these figures.

Table 5.10 Clegg hammer results derived from multiple regression coefficients in Table 5.9. Clegg hammer gravities that match target gravimetric moisture content (18-20%) and dry bulk density (1.65-1.75 g cm^{-3}) proposed by Adams *et al* (2004).

Clegg g	moisture %	density g cm^{-3}
402	18	1.65
439	18	1.75
369	20	1.65
406	20	1.75
335	22	1.65
372	22	1.75

This relationship demonstrates the sensitivity of hardness to moisture and dry bulk density and that there is more than one way to achieve the stated targets. To convey this to groundsmen, presentation in a three dimensional format provides a better visual representation of the relationship (Figure 5.22).

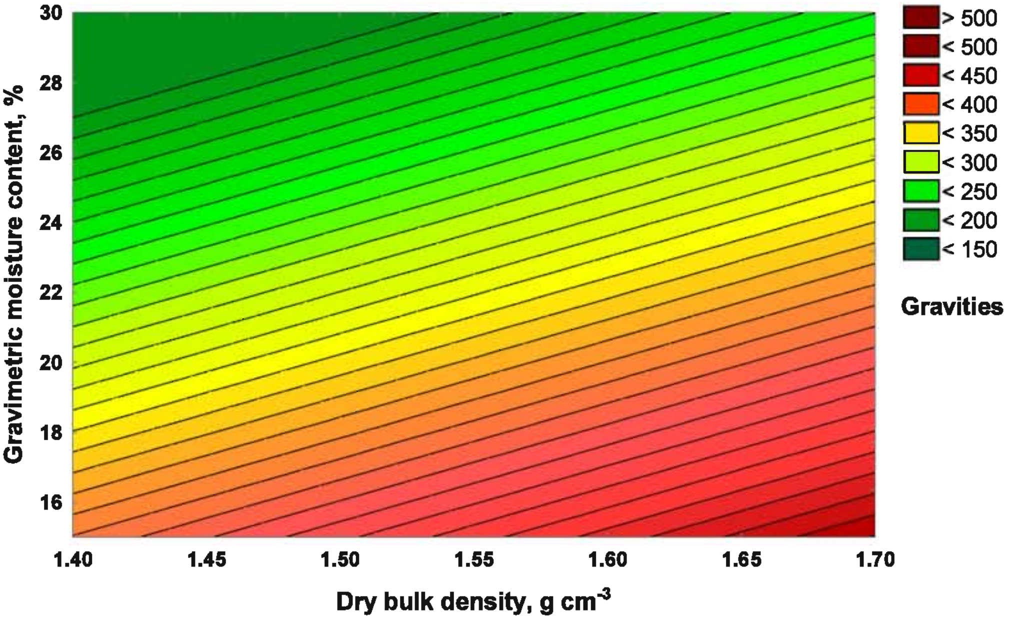

Figure 5.22 Three dimensional contour plot of Clegg hammer gravities against dry bulk density and gravimetric moisture content derived from regression coefficients from Table 5.9. An increase in density and/or a reduction in moisture content increase gravities.

This data to a large extent reinforces suggested gravimetric moisture content and dry bulk density targets already stated by Adams *et al* (2004) but whilst using a 0.5 kg Clegg hammer. It also provides a greater understanding of the relationship as well as a wider range of data points for practical use.

5.3.8.2 Ball Rebound

Analysis of ball rebound data for the 0-50 mm depth determined correlations separately between rebound and gravimetric moisture content and rebound and density with R^2 values of 0.59 and 0.64 respectively. Combining the two variables in a multiple regression model determined a significant** correlation with an R^2 value of 0.81 (Table 5.11).

Table 5.11 Multiple regression model for all ball rebound (rebound %). Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variables	Beta	Regression coefficient	p value
Intercept	-	-30.2207	0.014
Moisture	-0.485	-1.3188	<0.001
Density	0.553	44.6977	<0.001
Summary statistics			
Multiple R	0.904		
Multiple R^2	0.817		
Adjusted R^2	0.808		
F(2,39)	87.274		
p value	<0.001		

No significant differences were determined between soil types. This linear relationship is presented in Figure 5.23.

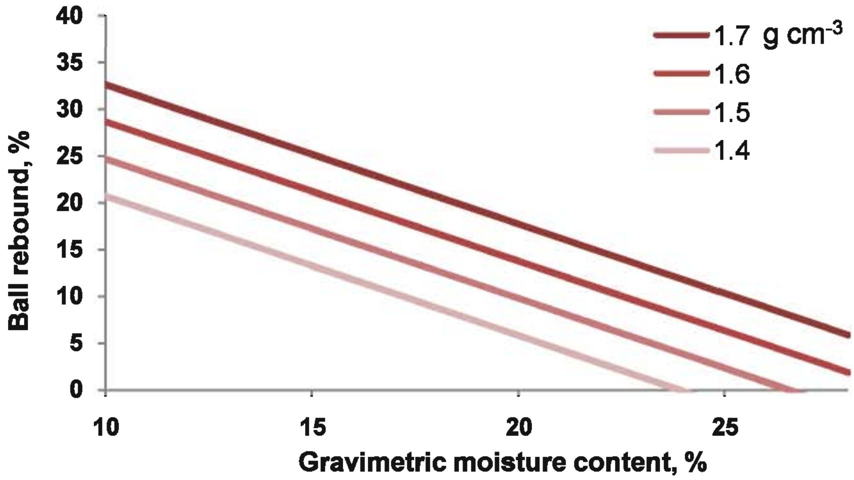

Figure 5.23 Linear relationship between Ball rebound percent (% of 3 m drop height) and gravimetric moisture content.

As soil moisture content declines the soil strength increases and plastic deformation reduces. Rebound will increase as a result of a reduction in energy lost to soil deformation and higher retained energy by the ball or return of energy to the ball. However reduction in soil moisture will result in shrinking in clay soils which will at some stage result in soil cracking which could reduce rebound height and consistency. It is therefore unlikely that this relationship is linear as soil moisture declines beyond the limits of moisture content tested here. Also, decline in moisture content is restricted by permanent wilting point which is approximately 17% to 18% for a soil at a dry bulk density of 1.60 g cm^{-3} and 16% to 17% for a soil at a density of 1.40 g cm^{-3} for KL and OL soil respectively (see Section 6.4).

5.3.8.3 Cracking

Analysis of soil cracks resulting from naturally drying the compacted KL and OL soils in the experimental plots was undertaken during Experiment 4 (August 2007). Each of the 20 plots was scored for cracks daily during Experiment 4 and then at three day intervals for a further 9 days, covering a 23 day drying period. These results were correlated with moisture content measurements taken on the same day and dry bulk density after 4 days of rolling but before cracking occurred. Dry bulk density was fixed at the day four level to determine the cracking of a soil based on its initial density. Day four was determined in Experiment 4 to be the point where no further increases in dry bulk density occurred due to rolling and therefore from a pitch preparation perspective the maximum achievable dry bulk density from the roller used. Cracking is a result of the initial soil bulk density. Cracking itself reduces the soil dry bulk density in a given area of soil however soil core sampling may selectively miss soil cracks with results therefore being a reflection of dry bulk density between soil cracks.

No significant difference was determined for soil type however a significant** multiple regression model of soil cracking with moisture and dry bulk density as variables was derived with an R^2 value of 0.69 (Tables 5.12).

Table 5.12 Multiple regression model and summary statistics for soil cracking score. Moisture variable on the day of cracking score and dry bulk density variable measured as the initial density after rolling and before excess drying. Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variables	Beta	Regression coefficient	p value
Intercept	-	40.9919	<0.000
Moisture	-0.815	-0.5242	<0.001
Density	-0.604	-19.4532	<0.001
Summary statistics			
Multiple R	0.833		
Multiple R^2	0.694		
Adjusted R^2	0.689		
F(2,129)	146.22		
p value	<0.001		

Although the crack score is an ordered categorical variate, probit or logistic analysis was not appropriate due to the large number of measurements with a zero score which would result in a prediction of a negative cracking score. Although the linear multiple regression model assumes the scores are continuous variables, the assumptions required to fit the normal linear regression were satisfied i.e. the residuals were normally distributed and data points on the residuals against observed plot were evenly scattered around the zero residual line. This method did however require the rounding of predictions to the nearest category.

Plotting of dry bulk density in a three dimensional format against cracking score and gravimetric moisture content indicates an increase in the cracking score as soil moisture reduces (Figure 5.24).

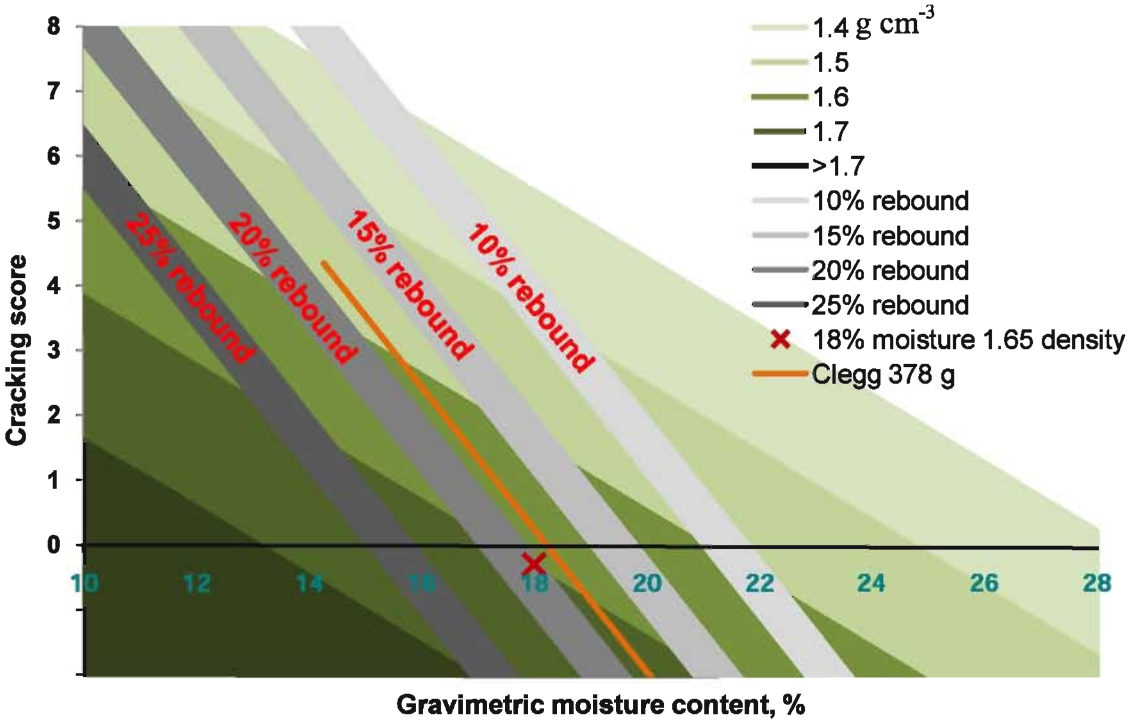

Figure 5.24 Three dimensional plot of initial dry bulk density (after rolling) against gravimetric moisture content and soil cracking score. Ball rebound superimposed in relation to density and moisture from regression model in Table 5.10. Reduction in soil gravimetric moisture content increases the propensity for an increase in soil cracking score. A higher initial density reduces the cracking score for a given moisture content. Ball rebound increases with a reduction in soil moisture content but a lower soil density requires a lower soil moisture content to achieve the same degree of rebound. Clegg 378 g denotes Clegg hammer data derived from regression model in Table 5.9 and relates to relevant density and moisture content and is equal to 18% ball rebound. Points below zero on the y axis are relevant for rebound, dry bulk density and gravimetric moisture. Point X indicates moisture and density targets suggested by Adams *et al* (2004).

Lower moisture contents are tolerated by higher bulk density soils before a given level of cracking score is attained. This does not necessarily indicate fewer cracks in the higher bulk density soil because the score relates as much to crack width as the quantity of cracks; therefore a high bulk density soil may have a high level of fine cracks which would be less detrimental to pitch playability than wide cracks.

Superimposing ball rebound data derived from the regression model in Table 5.11 in relation to dry bulk density and gravimetric moisture content onto Figure 5.24 provides a diagnostic tool for groundsmen to assess target moisture and dry bulk density in relation to playability factors ball rebound and pitch cracking.

Data was collected from soils that were eventually dried excessively to give extreme cracking scores. For practical pitch application it would be envisaged that a crack score above 2 (depending on an individual's view and match status) would not be an acceptable starting quality although pitch cracking is not categorised in PQS standards (Appendix 1).

The suggested targets for gravimetric moisture content and dry bulk density (Adams *et al,* 2004; 18% to 20% moisture and 1.65 g cm^{-3} to 1.75 g cm^{-3}) indicate a ball rebound of 19%. Suggested target rebound is 18% and therefore this diagnostic model concurs with Adams *et al* in this respect.

Combining predictions made by the regression models of ball rebound and the Clegg hammer (Tables 5.9 and 5.11) a linear regression relationship was derived:

Rebound % = 0.1115 x Clegg (g) -26.254

Examples of the results of this are presented in Table 5.13.

Table 5.13 Relationship between ball rebound and Clegg derived from regression models in Tables 5.9 and 5.11 for the same soil moisture and dry bulk density.

Ball rebound %	Clegg g
10	325
15	370
20	415

This relationship is based on regression models and did not result directly from field measurements. Correlation in the field was inconsistent and did not provide a reliable association particularly in the drier soils. Coefficients of $R^2 = 0.58$ reflected the inconsistency and concur with Baker *et al* (2001b) on the level of accuracy of the 0.5 kg Clegg hammer on cricket pitch soils.

5.3.8.4 Surface evenness

Surface evenness was assessed during Experiment 1. The experimental plots had not been rolled before and were therefore more uneven than would be normal during pitch preparation. A significant** increase in the level of evenness, as measured by the mean distance below a 0.5 m straight edge, occurred for KL soil up to 14 roller passes and for OL soil up to 12 roller passes (Figure 5.25).

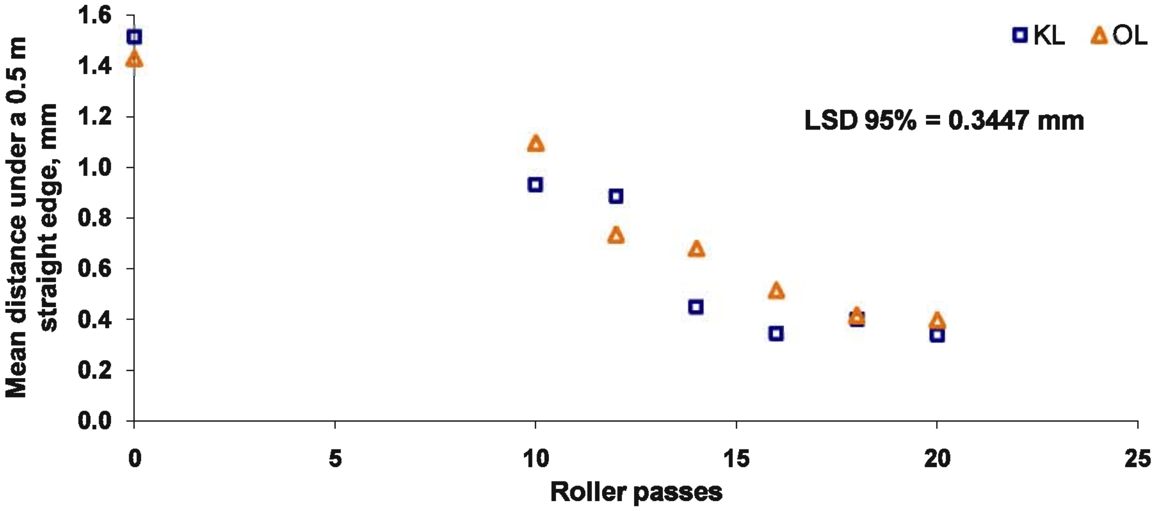

Figure 5.25 Surface evenness, measured by the mean gap beneath a 0.5 m straight edge, against roller passes for Experiment 1 using a 725 kg m^{-1}, 600 mm diameter two drum roller.

Due to the initial state of unevenness it is likely that 10-12 roller passes would be sufficient to maximise surface evenness from rolling however this experiment was not replicated to confirm this.

5.3.8.5 Summary of playability measurements

The relationship between Clegg hammer, ball rebound, moisture and bulk density has been developed and essentially reinforces the recommendations of Adams *et al* (2004). Targets dry bulk densities of 1.65 g cm^{-3} may be to the upper limit of most cricket rollers and this will be discussed further in a later section (Sections 5.4.1 and 8.2.3).

However at this density the target ball rebound of 18% should be achieved at moisture content below 20% (Table 5.14).

Table 5.14 Dry bulk density, moisture, ball rebound and Clegg hammer relationship.

Density g cm^{-3}	Moisture %	Rebound %	Clegg (0.5 kg) g
1.65	18	20	402
1.65	19	18	378
1.65	20	17	369
1.75	18	24	438
1.75	20	22	405

The relationship between cracking and the other playability parameters provides a basis for suggesting minimum moisture content before pitch playability is compromised. No significant differences were determined between KL and OL soil for soil cracking, Clegg hammer and ball rebound. This implies that playability is less dependent on soil type and more a reflection of dry bulk density and moisture content, although soil type will influence soil drying and the timing of effective rolling compaction.

5.3.9 Soil shear strength

Shear strength was measured by a shear vane during Experiments 1 and 2. This data provided no additional insight into increased soil bulk density resulting from rolling. Strength is affected by soil moisture as well as bulk density but in the field it is also affected by grass roots. Shear strength indicated strong correlations with gravimetric moisture content with a significant** difference between depths. Depth 0-30 mm correlated with moisture but not with other depths which is likely to be due to the additional strength provided by grass roots which is in agreement with Adams *et al* (1985), Tengbeh (1993) and others (Figure 5.26).

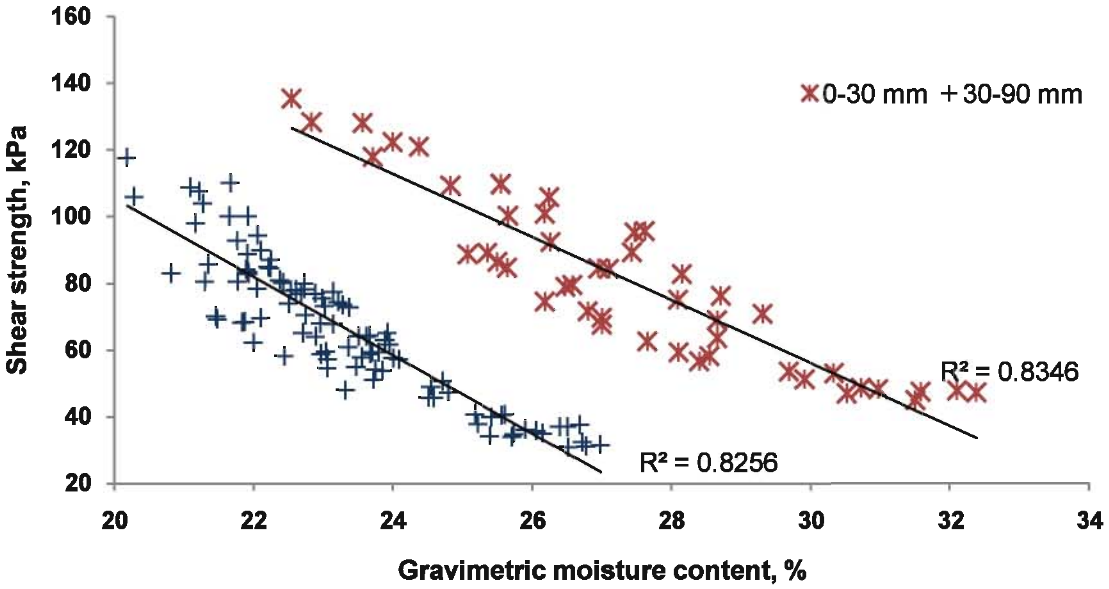

Figure 5.26 Shear strength correlation (as determined with a cruciform shear vane) with gravimetric moisture content for OL and KL soil. Depth 0-30 mm indicated higher shear strength at all moisture levels compared to combined data from 30-90 mm depth due to increase in strength provided by grass roots.

A multiple regression model determined a significant** relationship between shear strength (measured by a cruciform shear vane) and soil type, depth, dry bulk density and moisture content (Table 5.15). Beta coefficients in Table 5.15 indicate the relative importance of the explanatory variables; depth (due to grass roots) and being the most influential with soil type and dry bulk density having the least affect.

Table 5.15 Multiple regression model for shear strength (kPa), Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variable	Beta	Regression coefficient	p value
Intercept	-	245.170	<0.001
Soil type	-0.085	-3.994	0.025
Depth	-1.091	-54.165	<.001
Density	0.259	97.616	<.002
Moisture	-1.064	-9.199	<.003
Summary statistics			
Multiple R	0.947		
Multiple R^2	0.896		
Adjusted R^2	0.893		
F(4,139)	299.861		
p value	<0.001		

The shear vane as a measure of bulk density change from rolling in the field is restricted as the effects of grass roots and soil moisture will obscure any measure of bulk density change. Density also has a relatively small effect on shear vane measurements and furthermore at approximate moisture contents less than 21% and 22% (1.55 and 1.60 g cm^{-3} respectively) the equipment strength limit was exceeded which prevented its effective use in late spring or summer rolling experiments. As a measurement device for cricket pitches it therefore has limited applications.

5.3.10 Penetration resistance

Measurements of PR were taken in conjunction with moisture and dry bulk density cores during experiments on the plots for a range of soil conditions. PR is influenced by soil texture and soil physical conditions. A significant** multiple regression model was determined for PR with variables of dry bulk density and gravimetric moisture content (Table 5.16) however different soil type was not significant.

Table 5.16 Multiple regression model for penetration resistance (MPa). Explanatory variables are dry bulk density (ρ_d) and gravimetric moisture content. Beta = standardised regression coefficients indicating the relative importance of the explanatory variables.

Explanatory variables	Beta	Regression coefficient	p value
Intercept	-	4.7083	<0.001
Density	0.131	1.3309	<0.001
moisture content	-0.798	-0.22999	<0.001
Summary statistics			
Multiple R	0.872		
Multiple R^2	0.760		
Adjusted R^2	0.759		
F(2,473)	749.04		
p value	<0.001		

This model indicates that moisture content and soil dry bulk density can explain 76% of the PR measurement. The Beta coefficient indicates that moisture content accounts for 86% of this explanation. Presented graphically in a three dimensional contour plot the high level of influence of moisture content on PR is clear in comparison to soil dry bulk density (Figure 5.27).

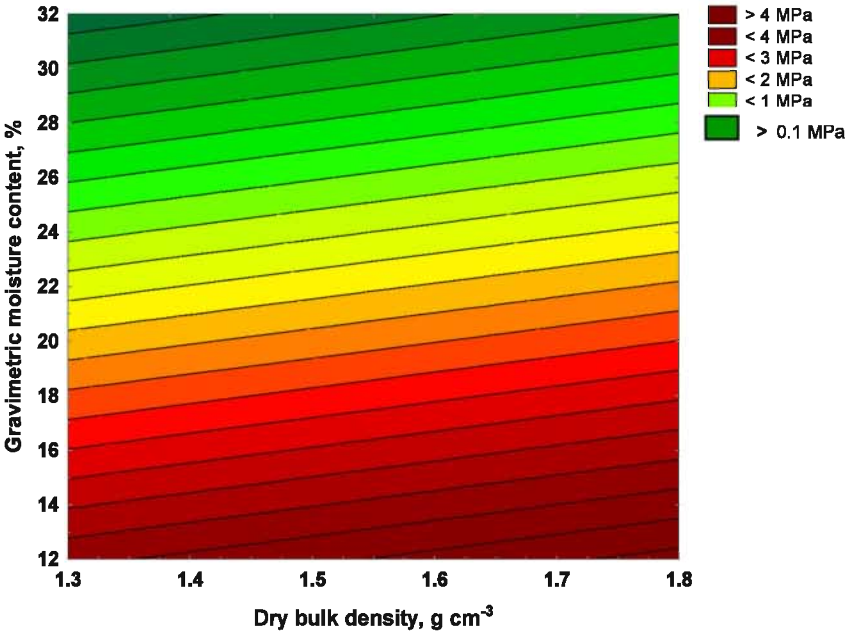

Figure 5.27 Three dimensional contour plot of penetration resistance (MPa) against dry bulk density and gravimetric moisture content derived from regression coefficients from Table 5.21. An increase in density and / or a reduction in moisture content increase PR.

As a measure of dry bulk density change from rolling PR has a limited use due to the influence of moisture content. Only in conditions of constant moisture content could dry bulk density change be assessed with any degree of accuracy. The relatively low influence of dry bulk density on PR compared to moisture content was also reported by Aggarwal (2006) who determined that moisture content accounted for at least 59% of the explanation of PR.

Measurements of dry bulk density were taken from the vicinity of the PR measurement and not the exact location (to avoid damage to the sample core) and this could lead to a slight variation in soil conditions between PR and dry bulk density and would account for some of the unexplained relationship.

The range of PR measurements did not reach the levels found by Ekwue *et al* (2006) in Trinidadian cricket soils with much higher clay contents (up to 80%). However the PR model is in agreement with Van Wijk (1983), who determined that a large increase in PR would occur below 20% moisture content. It is also in close agreement with Dexter's model of soil PR (Dexter *et al*, 2007; Section 1.5.4.2) which predicts PR would be 3 MPa at 17% moisture content on a sandy clay soil and also at 3 MPa for a

30% clay soil at a dry bulk density of 1.75 g cm^{-3}. Table 5.17 provides example PR results derived from regression coefficients in Table 5.16.

Table 5.17 Example PR results derived from multiple regression coefficients in Table 5.21. 3 MPa PR occurs at 17% moisture content for a soil dry bulk density of 1.70 g cm^{-3}.

	Gravimetric moisture content				
Density	16%	17%	18%	19%	20%
g cm^{-3}	MPa	MPa	MPa	MPa	MPa
1.4	2.89	2.66	2.43	2.20	1.97
1.5	3.02	2.79	2.56	2.33	2.10
1.6	3.16	2.93	2.70	2.47	2.24
1.7	3.29	3.06	2.83	2.60	2.37
1.8	3.42	3.19	2.96	2.73	2.50

Densities associated with cricket pitches after rolling (1.5 g cm^{-3} to 1.65 g cm^{-3}) have a predicted PR of approximately 3 MPa at moisture content below 17% which could have implications for root penetration. This is discussed in more detail in Section 8.3.5. The Dexter model predicts an increase in PR with an increase in clay content. However the difference between OL and KL soil clay content is only 5% for which the Dexter model would only predict a small difference in PR and therefore is in general agreement with these results.

5.4 Summary and discussion of field experiments

More than 9,000 soil samples were processed from approximately 1,800 soil cores taken from the trial plots between March 2006 and March 2008. Together with PR, Clegg hammer, ball rebound, shear vane and surface evenness measurements it has enabled an in depth investigation into the soil moisture and bulk density characteristics resulting from the rolling of two cricket soils.

5.4.1 Increase in cricket pitch bulk density

It was established in Chapter 4 that the maximum dry bulk density from a standard Proctor test was 1.68 g cm^{-3} for both the OL and the KL soil with an optimum gravimetric moisture content of 19.1%. From the field experiments and in general agreement with other work it was determined that for a 600 mm diameter roller to a depth of 30 mm, 92% of this dry bulk density was achievable with a 725 kg m^{-1} and

95% with a 920 kg m^{-1} roller. This equates to 1.55 g cm^{-3} and 1.61 g cm^{-3} dry bulk density. Optimum moisture at 5% air voids for these densities is therefore approximately 24% and 22%. From this it follows that a particular roller mass has an optimum moisture content in order that it can achieve its for maximum compaction potential.

The experiments determined that increase in dry bulk density in the depth 30-60 mm was 90% of Proctor optimum using a 920 kg m^{-1} roller, however in general this density already existed in the soil profile. In the work of Parsons (1992) this was achieved with a 500 kg m^{-1} roller. Increases in density to 100 mm which was suggested by Parsons as being possible with a 1000 kg m^{-1} roller was not determined (i.e. 1.51 g cm^{-3}) but again the profile was already at this bulk density.

Rolling with a roller of 920 kg m^{-1} (e.g. 2200 kg; 2 drum; 1.2 m wide; 600 mm diameter) is likely to achieve a dry bulk density below the current targets of 1.65 – 1.75 g cm^{-3} (Adams *et al*, 2004). Further increase in bulk density will result from drying but rolling alone will not achieve these densities.

The field experiments determined no increase in dry bulk density from rolling with a 130 kg m^{-1} roller in soil at a density between 1.39 g cm^{-3} and 1.45 g cm^{-3} with air voids up to 7%. Parsons (1992) indicates that achievable dry bulk density is 80% of Proctor optimum for a roller twice the size (250 kg m^{-1}). For the experimental soils, 80% equates to 1.34 g cm^{-3}. It can therefore be assumed that only densities below this figure are likely to be compacted with a roller of less than 250 kg m^{-1}, such as a grass mower. Decompacted or newly constructed pitches, or low bulk density pitches after expansion from saturation, may be at densities below 1.30 g cm^{-3} and some increase in bulk density could occur in the 0-30 mm depth from very light rollers (less than 250 kg m^{-1}).

5.4.2 Soil moisture

When using a roller with a compactive potential below the standard Proctor test maximum dry bulk density, rolling at a gravimetric moisture content above the standard Proctor optimum moisture will increase particle lubrication and reduce friction enabling higher maximum density to be achieved. At a dry bulk density of 1.61 g cm^{-3} and a gravimetric moisture content of 22% a cricket soil will have approximately 5% air voids therefore not restricting the level of compaction. 22% moisture content is 2.9% above the Proctor optimum moisture content. This concurs with Parsons (1992) who presented data indicating that for a roller mass <1000 kg m^{-1} rolling a sandy clay soil an increase in gravimetric moisture content by up to 4% above Proctor optimum moisture was beneficial in increasing maximum dry bulk density.

Reducing moisture below 22% will increase the force required to compact the soil and may reduce the maximum bulk density achieved. Moisture content above 22 % when the soil approaches maximum compaction could reduce the maximum achievable dry bulk density i.e. at 1.60 g cm^{-3} the soil will be saturated at 25% moisture content.

This presents a narrow range of moisture contents to achieve maximum potential dry bulk density and this will also depend on achievable density with a roller configuration.

Experiments determined that the higher the soils dry bulk density the lower the initial moisture content but the rate of drying was slower. These lower moisture contents were maintained throughout the drying period of 14 days both in the experimental plots and the grass rooting experiment. A higher bulk density soil will have reduced hydraulic conductivity rates and lower saturation moisture content due to the reduction in porosity and pore size. This will have consequences for spring and pre-match rolling in terms of the timing of rolling operations.

Winter expansion was shown to reduce dry bulk density significantly in the 0-90 mm depth, and particularly in the 0-30 mm depth, leading to an increase in soil voids which will result in higher saturation moisture content. Expanded soil in the top 0-60 mm after the winter will have high saturation moisture content but will dry more quickly from evapotranspiration. Drainage may be greater but will be dependent to a large extent on the bulk density of soil below.

The OL soil had a slower drying rate and held more moisture during spring compared to the KL soil and therefore the necessity for early rolling is greater in the higher clay content soil.

Soil shrinkage in the 0-60 mm depth did not increase dry bulk density by the same amount as the reduction in density caused by soil expansion, justifying the need for rolling. This was generally not the case for greater depths due to the overburden stress helping to re-consolidate the soil as it dries. Shrinkage was shown to equate to approximately an increase in dry bulk density of 0.0125 g cm^{-3} for a 1% reduction in moisture content.

Pre-match rolling following saturation of the soil has much in common with spring rolling apart from the speed of drying. Saturation will reduce bulk density as the soil expands and drying will gradually increase bulk density as the soil shrinks. Higher initial bulk densities particularly in depths below 60 mm will reduce the initial saturation moisture content and field capacity watering and these depths will remain drier as the profile dries. As the depth in the profile increases the rate of drying will decrease. The 0-30 mm depth will experience the greatest change in moisture content. Higher initial moisture content at this depth after irrigation or rainfall is likely to be a reflection of soil expansion in the 0-60 mm depth due to an increase in the void ratio. This is followed by faster drying rates resulting from proximity to the surface allowing for greater evaporation. Final moisture contents after 14 days drying were not significantly different among different bulk density treatments in the 0-30 mm depth.

The rate of drying will depend on the weather conditions which affect grass growth and evaporation. Low grass growth in the spring together with high rainfall and high humidity will result in high soil moisture content and slow drying rates. OL soil remained between 0% and 2% air voids throughout all of the early spring in 2006 resulting in no indication of an increase in bulk density from rolling. The KL soil was drier in early spring allowing for an increase in bulk density from rolling with initial air voids of 7%. During the spring of 2007 soil moisture was lower with both soils at a minimum of 4% air voids.

5.4.3 Roller passes

Differences in compaction rates with regard to roller passes occurred throughout the rolling experiments and were not always consistent, depending on bulk density and moisture content. When the potential bulk density increase is high and moisture content is close to optimum (i.e.22% to 24% gravimetric moisture content) increase in density will be rapid in terms of the number of roller passes required. Smaller increases occur when the soil moisture is lower than optimum but still within the rollers capacity to increase bulk density. This concurs with Parsons (1992) work who determined that an increase in moisture content up to 4% above the Proctor optimum moisture reduced roller passes by more than 50%.

The overall mean increase in dry bulk density per roller pass (two drum roller) for the field rolling experiments, when density increase was a direct result of rolling, was 0.015 g cm^{-3} (0.0075 g cm^{-3} per roller drum). This figure was not statistically consistent but does provide a basis for calculating the required number of roller passes. After saturation for match preparation the required passes to increase dry bulk density from 1.45 g cm^{-3} to 1.60 g cm^{-3} would therefore be a maximum of 10 roller passes (two drum roller). For small incremental increases in the spring as part of a programme of gradual increase in dry bulk density an increase of 0.05 g cm^{-3} would require four roller passes. These figures are consistent with the roller passes required to increase dry bulk density in the field rolling experiments. They are also consistent with the DSIR (1951) who determined fast rates of density increase from an initial soil dry bulk density of 1.10 g cm^{-3} up to 1.50 g cm^{-3} and then a rapid decline in the rate of density increase for successive roller passes. They determined that after 1.50 g cm^{-3} dry bulk density it required six passes of the roller to compact a similar soil to 1.60 g cm^{-3}, equivalent to 0.017 g cm^{-3} per roller pass (2 drum roller). Densities below 1.45 g cm^{-3} will probably increase at a faster rate with the same 725/920 kg m^{-1} roller but this rate may be reduced with a lighter roller.

Roller experimental treatments used different pass combinations which were not determined to affect final densities achieved. Any differences that occurred were a result of moisture content and not roller passes. In the pre-match rolling experiment frequency of rolling had no effect on dry bulk density and therefore rolling in the later stages of pre-match preparation after maximum dry bulk density has been achieved will need to be justified for reasons other than increasing soil bulk density. Current guidelines (ECB, 2007) suggest the futility of rolling ‘once all the moisture has gone from the pitch’ and in terms of increasing soil bulk density these experiments would agree with this sentiment albeit with a more scientific reasoning. However other playability factors need to be considered i.e. grass leaf moisture content, which may require some form of rolling management to achieve the desired condition. This aspect of pitch preparation has not been part of this study.

5.4.4 Speed

Rolling speed was assessed during Experiment 3 and no difference in dry bulk density increase was determined between the two speeds of 0.35 km h^{-1} and 0.7 km h^{-1}. The soil bin rolling experiment (Chapter 4) also determined no difference in dry bulk density between speeds of 1 km h^{-1} and 2 km h^{-1}. Parsons (1992) showed a reduction in dry bulk density increase per roller pass as speed increased but this was generally recovered with more roller passes. As an example of Parsons results, a 3.9 ton towed roller indicated the difference in density between 0.5 km h^{-1} and 2.3 km h^{-1} was 2% of optimum in favour of the slower roller (approximately 0.03 g cm^{-3}) after 2 roller passes but the difference was negligible by 16 passes.

5.4.5 Playability results

Playability measurements Clegg hammer and ball rebound were found to be strongly influenced by soil moisture content. This reduced their contribution to the assessment of rolling efficiency in conditions of changing moisture.

Significant** linear regression models predicting Clegg hammer (0.5 kg hammer), ball rebound (3 m drop height) and soil cracking were derived from explanatory variables gravimetric moisture content and soil dry bulk density. All of these models indicated a high correlation with moisture content and a relatively low correlation with dry bulk density however no significant differences were determined between KL and OL soil for soil cracking, Clegg hammer and ball rebound.

The relationship between ball rebound and soil cracking was developed using the soil parameters of moisture and dry bulk density. Ball rebound of 18% was predicted to occur at a Clegg hammer measurement of 378 g at the target density of 1.65 g cm^{-3} and at 19% moisture content. In general this reinforces the recommended targets of Adams *et al* (2004) (1.65 g cm^{-3} to 1.75 g cm^{-3} dry bulk density; 18% to 20% gravimetric moisture content). Clegg hammer predictions were not comparable to Adams *et al* due to the different Clegg hammer configurations used. These levels of dry bulk density were not achieved by the compactive force of the standard ballasted cricket roller (920 kg m^{-1}) and drying after rolling is required to meet the playability targets.

The rebound and cracking models are based on dry bulk density prior to drying to coordinate with rolling targets and are not a reflection of final bulk density achieved on match days which will be higher due to shrinkage. The current targets are presumably for match day densities and it is likely that shrinkage after rolling will go some way to enabling them to be achieved.

This combination of models provides a fuller understanding of the relationship between moisture, dry bulk density and pitch cracking yet is in broad agreement with current targets. The relationship between cracking and the other playability parameters also provides a basis for suggesting minimum moisture contents. This could be used as a tool for groundsmen to assess target moisture and dry bulk density in relation to playability factors, ball rebound and pitch cracking. It could also be of value to assess potential limits for pitch preparation and also as a means for diagnosing recurring problems of inadequate pitch performance.

Correlation of ball rebound with the 0.5 kg Clegg hammer was low which was in agreement with Baker *et al* (2001b). Reliability and cost would favour use of the ball rebound technique as consistency with Clegg measurements was considered no better than visual measurement of rebound. The cost of the Clegg hammer equipment is likely to be prohibitive for most facilities and as a tool for groundsmen to measure potential pitch performance a 3 m drop is easy and cheap to improvise.

5.4.6 Shear vane and penetration resistance.

The regression model for the shear vane measurements determined moisture content, soil depth, dry bulk density and moisture to be significant explanatory variables for shear strength. The significance of depth was attributed to the influence of grass rootmass in the 0-30 mm depth which was confirmed in the rooting experiment where it was determined that between 47% and 68% of rootmass occurred in the 0-50 mm depth. Equipment limitations in compacted soil below 22% moisture and the influence of moisture content and roots make this equipment unsuitable for use in cricket pitch management particularly when assessing roller performance.

The PR model determined that moisture content strongly influences PR and that dry bulk density although it was significant had a limited influence on PR in the range of densities tested (1.30 g cm^{-3} to 1.75 g cm^{-3}).

Use of penetration resistance by groundsmen whether by actual measurement or by intuitive feel will give an indication of moisture content more than bulk density. Many groundsmen use this method for determining time for spring rolling and should be made aware of what they are measuring. Use as an indicator of dry bulk density and the need for rolling could be misleading.

PR increased to 3 MPa below 17% to 18% moisture content at soil dry bulk densities above 1.70 g cm^{-3} and for soil density 1.50 g cm^{-3} to 1.60 g cm^{-3} this occurred at 16% to 17% moisture content. This level of resistance has been shown by others to affect root penetration into the soil and reduce plant growth in monocotyledonous plants. It is therefore likely that most cricket pitches will at some point restrict root growth or alter root distribution but this is most likely to occur during the summer months when soil moisture falls below critical levels.

Pitches reseeded in the autumn will require moisture content in excess of 19% to 20% to ensure mechanical resistance to root growth is not restricting root penetration. Winter months are likely to provide adequate moisture and give a PR of less than 2.5 MPa in soils up to 1.80 g cm^{-3} potentially enabling new roots to penetrate into the pitch profile.

Chapter 6. Grass rooting in compacted cricket loams

6.1 Introduction

The extent to which grass roots can penetrate compacted cricket soils and their influence on pitch profile drying has not been previously established. Grass leaf and roots have important functions in pitch preparation and playability parameters and an understanding of the limitations of rooting in compacted soils will help to establish an upper limit to pitch dry bulk density. This will also inform the debate on the necessity for pitch aeration.

Designing an experiment to determine root growth in a compacted clay loam also provides an opportunity to determine the rate of drying of a soil from saturation in a pre-match cricket scenario. This provides valuable information for determining the optimum timing of rolling and potential pitch playability.

Plants remove water from the soil by osmosis as a result of creating a chemical concentration gradient between the root and the soil water that is in the soil pores (Taiz & Zeiger, 2002). This in turn sets up a physical potential pressure gradient. The more tightly the water molecules are held within the soil pore, the greater the tension (negative pressure) required by the plant to remove the water. The degree to which water is held within the soil matrix is dependent on the total amount of water and the average pore size within the profile; soil with a smaller average pore size will require greater tension for the water to be removed. Using pressure membranes in the laboratory to apply tension to a soil sample it is possible to examine this relationship for different soils and for soils compacted at different densities. This gives a laboratory based measure to be compared to the drying rates achieved during the rooting experiment and trial plot experiments (Section 5.3.5.1).

6.2 Grass rooting in compacted cricket loams: methodology

Samples were prepared in September 2006 by evenly packing soil into tubes 100 mm diameter x 300 mm length. The five dry bulk density targets were 1.2, 1.4, 1.6, 1.8, 1.9 g cm^{-3}. The initial dry bulk density of the treatments 1.8 g cm^{-3} and the 1.9 g cm^{-3} fell short of the target density due to difficulties achieving these densities manually.

There was also a slight difference in dry bulk density between soils, 1.77 g cm^{-3} and 1.74 g cm^{-3} for KL and OL respectively for the 1.8 g cm^{-3} treatment and 1.86 g cm^{-3} and 1.83 g cm^{-3}for KL and OL respectively for the 1.9 g cm^{-3} treatment. In addition to the specified densities, two further treatments were prepared with two layers of different dry bulk density within the same sample to simulate the effect of reduced compaction in the top 100 mm. These treatments had a dry bulk density of 1.40 g cm^{-3} over 1.60 g cm^{-3} and 1.60 g cm^{-3} over 1.80 g cm^{-3}. All densities were repeated in the two clay loam soils, OL and KL as described in Section 4.2.1. All samples were replicated five times. Three sets of replicates were seeded with a mixture of perennial ryegrass (*Lolium perenne*) varieties Ace, Tucson, Greenflash and Greenway which was seeded at 35 g m^{-2}. Pre-seed fertiliser (5:10:5, $N:P_2O_5:K_2O$) was applied at 50 g m^{-2}; a spring fertiliser (20:5:15) was applied at 35 g m^{-2} on 25/03/07. Two samples of each soil type were maintained as soil-only controls. After germination grass height was maintained at 20 mm. The tube length was protected from temperature extremes with fibre insulation but the surface was permanently exposed to natural climatic variation. Moisture content was maintained with natural precipitation resulting in no observed shrinkage of the sample away from the tube wall during the growing period.

Moisture content dynamics and grass growth were measured over a 16 day test period in June 2007. This was a time period that fits within the normal range of pre match pitch preparation practice. All samples were saturated by immersion at the start of the test for 48 hours and subsequently weighed daily between 10.00 am and 12.00 noon for the period using a 0.01 g precision balance. The assumption made was that daily weight loss is attributable to change in moisture content although a small amount of grass growth also occurred.

Samples were also taken to measure moisture content by oven drying at 4 depths, 0-50, 50-100, 100-150, 150-200 mm, every 4 days.

Grass length was cut to 12 mm for the test duration and excess growth was cut and oven dried to record dry matter produced.

At the end of the 14 day drying period a 15 mm diameter core was extracted from each tube to determine soil microbial biomass[3]. A second 42 mm diameter x 150 mm deep core was extracted from the centre which was cut into 4 x 50 mm sections for the assessment of root biomass. These samples were washed to remove the soil from the roots and then the roots were dried at 80°C for 18 hours. Weights were recorded prior to incineration at 500°C for 30 minutes and ash weights were subsequently recorded and deducted from dry weight to give figures of ash free root weight. No edge effects were observed for preferential root growth between the sample and the tube wall and final root samples were taken from the tube centre to avoid any preferential bias.

Water release characteristics for the two soils detailed in Section 3.2.2 were determined in duplicate for four different levels of dry bulk density i.e. 1.2, 1.4, 1.6, 1.8 g cm^{-3} following the Cranfield University method NR-SAS/SOP 24/1. After saturation, the samples were placed on a sand table and held at three separate tensions (1, 5 and 10 kPa) and then placed in the pressure membrane apparatus at five separate tensions (100, 200, 400, 800 and 1500 kPa). Each tension was applied for approximately 10 days. Sample weights were recorded for each level of tension. After the final tension period the samples were weighed and then oven dried at 105°C for 48 hours. Calculations were then made to determine soil moisture content at each level of tension for each sample and the results were subjected to a statistical analysis of variance to a significance level of $p < 0.05$.

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[3] The soil microbial sampling and subsequent analysis was carried out by Dr Mark Bartlett, Cranfield University.

6.3 Grass rooting in compacted cricket loams: Results

6.3.1 Root mass

Total rootmass for depth 0-200 mm indicated significant** differences between treatments and soil type (Figure 6.1).

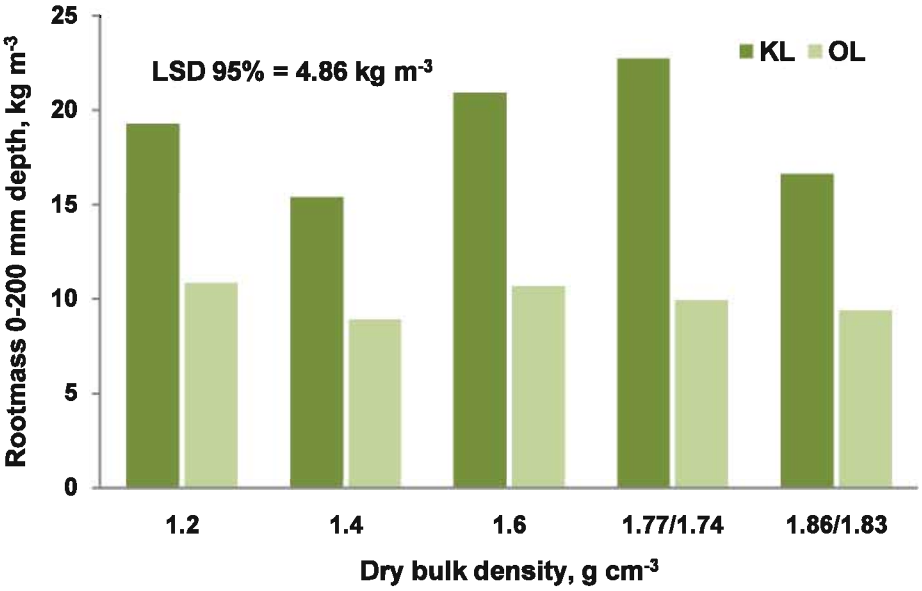

Figure 6.1Ash free rootmass for KL and OL soils, 0-200 mm depth. KL soil had significantly greater rootmass for each of the treatment densities compared to OL soil.**

KL soil indicated significantly** greater rootmass for all treatments compared to OL soil. An increase in rootmass occurred between the 1.40 g cm^{-3} treatment compared to the 1.77 g cm^{-3} and a decline in rootmass from 1.77 g cm^{-3} to 1.86 g cm^{-3}. The OL soil indicated no significant differences between treatments.

Rootmass declined significantly** between 0-50 mm and 50-100 mm at all levels of dry bulk density and for both soils. Further significant** declines in rootmass occurred between 50 mm and 200 mm in the KL soil for the 1.77 g cm^{-3} and 1.86 g cm^{-3} treatments (Figure 6.2).

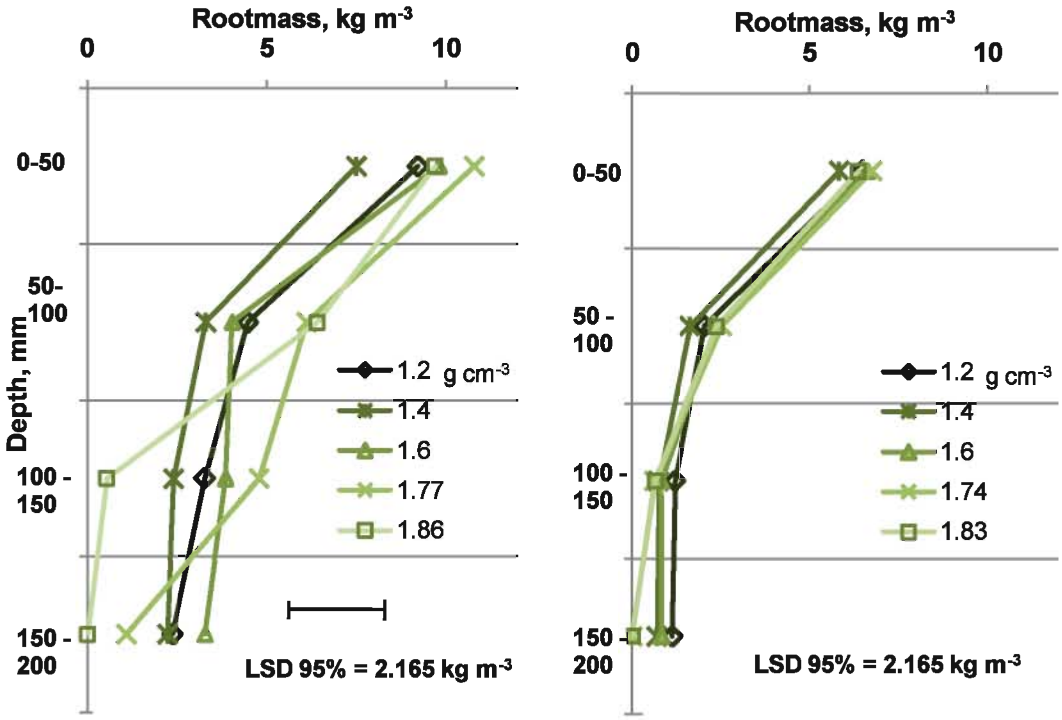

Figure 6.2 Rootmass by depth. KL soil (left) indicated greater rootmass at all depths when compared to OL soil (right).

KL soil had greater rootmass at all depths compared to OL soil although this was not consistently significant. Concentration of rootmass in the 0-50 mm depth was also significantly** different between soils with the OL soil having a greater percentage of the total roots measured in the 0-50 mm depth. Differences within soil type were not significantly different with the exception of the KL soil 1.86 g cm^{-3} treatment which had significantly** greater rootmass compared to the other KL treatments.

Root growth was shown to be more influenced by soil type than soil dry bulk density. Higher rootmass at all densities occurred for the KL soil compared to OL soil. The two soils had different particle size distributions. A higher particle size will result in a higher average pore size which will influence root growth in a compacted soil not only from differences in mechanical resistance but also changes in the physical environment affecting nutrient and oxygen availability (Boone, 1988). The median particle size (D_{50}) for KL soil was 45 µm compared to the OL D_{50} of 11 µm (Figure 6.3).

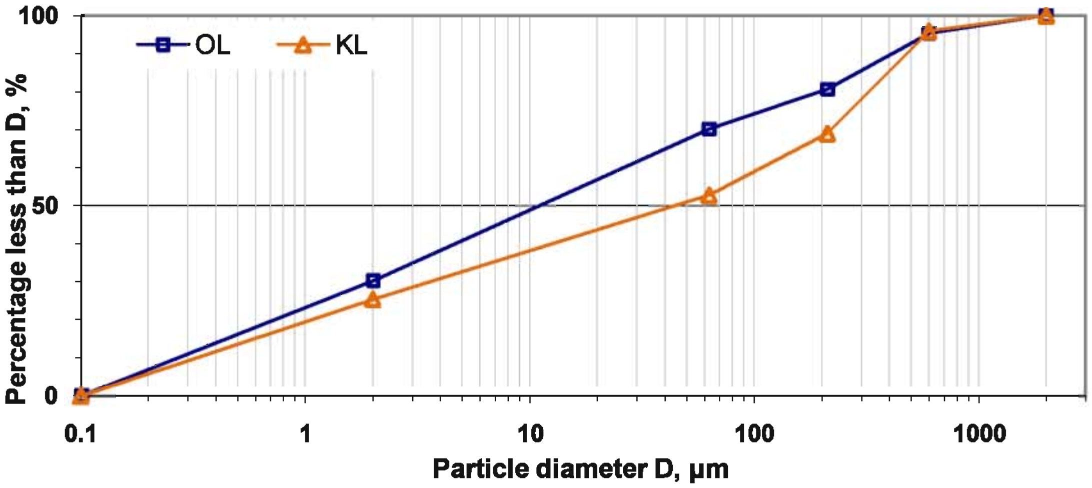

Figure 6.3 Soil particle size distribution for KL and OL soils. The median particle size (D_{50}) for KL soil is greater than OL soil reducing root impedance due to higher average pore size.

Dexter (2007) determined an increase in PR resulting from an increase in soil clay content which was related to the pore structure within the soil as well as the mechanical strength properties of clay. Baker (1998b) could not explain differences in rooting among seven cricket loams other than suggesting that soil dry bulk density and organic matter could account for the root difference. However the KL and OL soils had the same organic matter content (3%) and this was therefore not responsible for the difference in rooting in this experiment. Root distribution in cricket soils is therefore likely to differ between venues due to soil type particle size distribution and the range of cricket soils available rather than the soil dry bulk density.

The high percentage of rootmass in the 0-50 mm depth would imply greater strength in this zone compared to the sudden decrease in roots below this depth. This concurs with the increase in strength determined in the 0-30 mm depth for the shear vane results (Section 5.3.9). This could have implications for rolling due to the change in soil strength characteristics. Pitch drying could also be affected by the decline in moisture removal below 50 mm.

An increase in soil dry bulk density in the KL soil resulted in an increase in rootmass in the 50-100 mm depth for the 1.77 g cm^{-3} and 1.86 g cm^{-3} treatments compared to the other densities. This also occurred in the 100-150 mm depth for the 1.77 g cm^{-3} treatment causing an apparent upward transfer in rootmass distribution as a response to increasing dry bulk density.

There was no significant reduction in rootmass in the whole 0-200 mm depth between 1.20 g cm^{-3} and 1.77 g cm^{-3} dry bulk density in the KL soil but there was a significant** decline in rootmass between 1.77 g cm^{-3} and 1.86 g cm^{-3}, a result of a more rapid decline in rootmass below 100 mm for the 1.86 g cm^{-3} treatment, to the point where no roots were observed in the depth 150-200 mm. Total rootmass for the 0-200 mm depth in the OL soil was consistent across all densities and for all depths.

6.3.2 Dual dry bulk density treatments

Dual dry bulk density treatments increased overall rootmass (in the 0-200 mm depth) when compared to the rootmass in a single density treatment that had a comparable dry bulk density to the density below 100 mm (i.e. comparing 1.60/1.80 g cm^{-3} with 1.80 g cm^{-3}). This increase was only significant** for the 1.60/1.80 g cm^{-3} dual dry bulk density treatment (Figure 6.4).

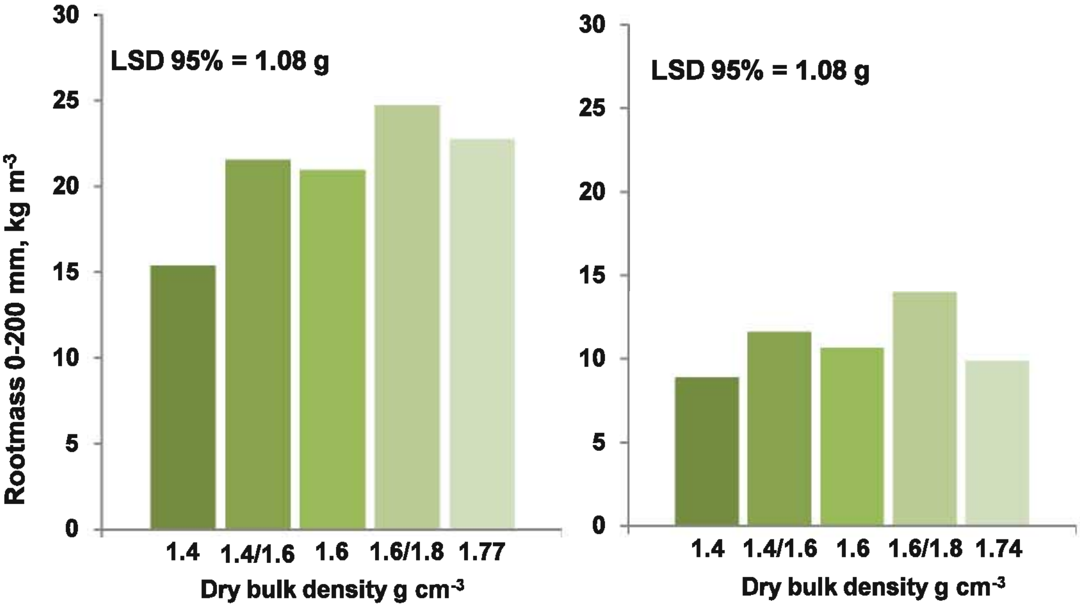

Figure 6.4 Rootmass in the depth 0-200 mm for dual dry bulk density treatments compared to single density treatments; KL soil (left) and OL (right). A significant increase in density was determined for dual density compared to single density treatments when comparing the 0-100 mm densities.**

Differences in rootmass at each depth indicated a change in root distribution resulting from the change in dry bulk density at 100 mm (Figure 6.5).

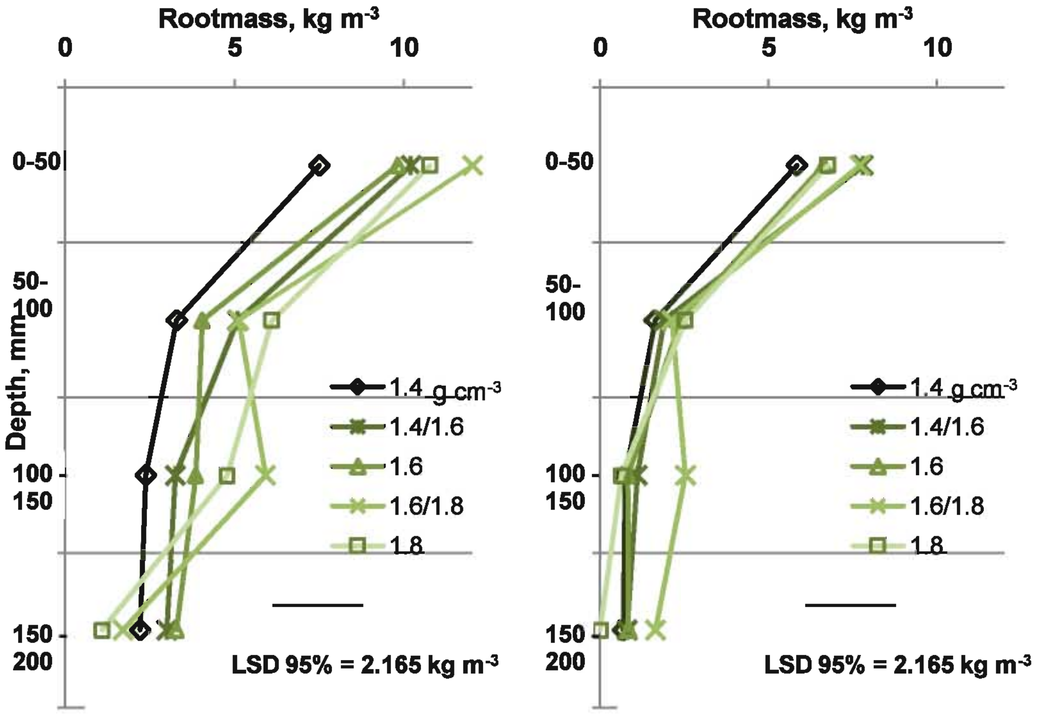

Figure 6.5 Dual dry bulk density rootmass by depth compared with single density treatments. KL soil (left) and OL soil (right).

The change in root distribution was more noticeable in the KL soil but not consistently significant. Rootmass on the dual dry bulk density treatments had a tendency to have increased rootmass in the depths to 150 mm, in particular an increase in the 100-150 mm depth where the roots proliferated into the denser soil. This was particularly the case for the 1.60/1.80 g cm^{-3} treatments although this was only significant** for KL soil. A more rapid decline in the 200 mm depth occurred below 150 mm for the KL dual treatments.

Summary of rooting characteristics

Figure 6.6 shows a schematic representation of the observed and measured changes in root distribution as a response to different bulk density conditions in KL soil.

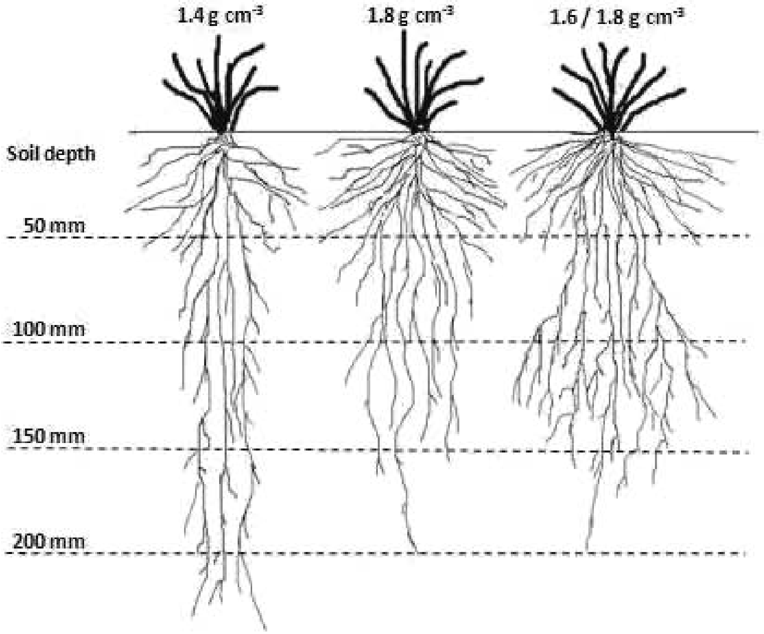

Figure 6.6 Schematic diagram of root distribution in the 0-200 mm depth in KL soil (drawn roots reflect data for rootmass). An increase in soil dry bulk density encourages grass roots to proliferate closer to the soil surface. Roots in 1.40 g cm^{-3} density (left) exhibited greater root depth overall but with less rootmass in the 0-50 mm depth compared to higher density treatments. Rootmass below 200 mm was not measured. Roots in 1.80 g cm^{-3} density soil (centre) produce greater rootmass in depths 0-50 mm, 50-100 mm and 100-150 mm compared to the 1.40 g cm^{-3} density soil. Roots in dual density treatments (right) indicated a significant increase in rootmass in the 100-150 mm depth as the roots encountered the higher density soil.

Points of note:

- Increased soil dry bulk density resulted in an increase in root growth closer to the soil surface and a reduction in root depth but not generally a reduction in total rootmass in the 0-200 mm depth
- Rootmass below 200 mm was not measured and therefore total rootmass of the plant may have been greater. However low levels of rootmass in the 150-200 mm depth for the KL 1.77 g cm^{-3} and the 1.86 g cm^{-3} treatments and all of the OL treatments would indicate very little rootmass occurred below 200 mm for these treatments.
- Rootmass in the top 100 mm increased as dry bulk density increased due to the change in the distribution or as a result of stimulation of rootmass from reduced pore size. Changes in root diameter were not recorded.
- Dual bulk density treatment 1.60 g cm^{-3} over 1.80 g cm^{-3} indicated an increase in rootmass in the 100-150 mm depth as roots encountered the higher density soil.

The change in dry bulk density within the profile stimulated root proliferation as the roots met with higher mechanical resistance. Compensatory root growth as a response to compaction has been determined in other crops tomatoes (*Solanum lycopersicum*), lettuce (*Lactuca sativa*) and broccoli (*Brassica oleracea*) (Mulholland, 1999; Montagu *et al,* 2007). The responses between soil types were similar but were more pronounced in the KL soil which consistently showed greater rootmass in all treatments and at most depths.

In Chapter 5 (Section 5.3.10) a PR of 3 MPa was predicted to occur on the KL and OL soils at approximately 1.70 g cm^{-3} at a moisture content of 17%. Previous work has determined that this is the approximate point at which monocotyledonous plants will begin to have inhibited root growth (Dexter, 1986c; Coelho *et al*, 2000). At higher moisture contents the PR model predicted PR at less than 3 MPa for soils of 1.80 g cm^{-3}. It can be concluded that rooting into compacted cricket soils of 1.80 g cm^{-3} is possible. However the moisture content will need to be above 17%. The approximate saturation moisture content of a 1.80 g cm^{-3} clay soil is 21% and therefore the range between too dry for penetration and too wet for healthy root growth is low. Sadras *et al* (2005) determined some root growth changes at PR levels below 3MPa and this experiment would concur with their findings due to the change in root distribution.

An upper limit of dry bulk density for pitch compaction was not determined but within the normal cricket pitch dry bulk density ranges (1.40 g cm^{-3} to 1.80 g cm^{-3}) density did not reduce potential rootmass in the top 150 mm although the distribution within the profile may change in favour of the shallower depths with an increase in bulk density.

6.4 Moisture removal from the root experiment

Moisture content was significantly** greater for lower dry bulk density treatments compared to higher density treatments throughout the drying period for both soils apart from the KL 1.77 g cm^{-3} and 1.86 g cm^{-3} treatments which were not statistically different from each other. Moisture content in the OL soil was also significantly** greater for all density treatments compared to the KL soil at all times during the drying process (Figure 6.7).

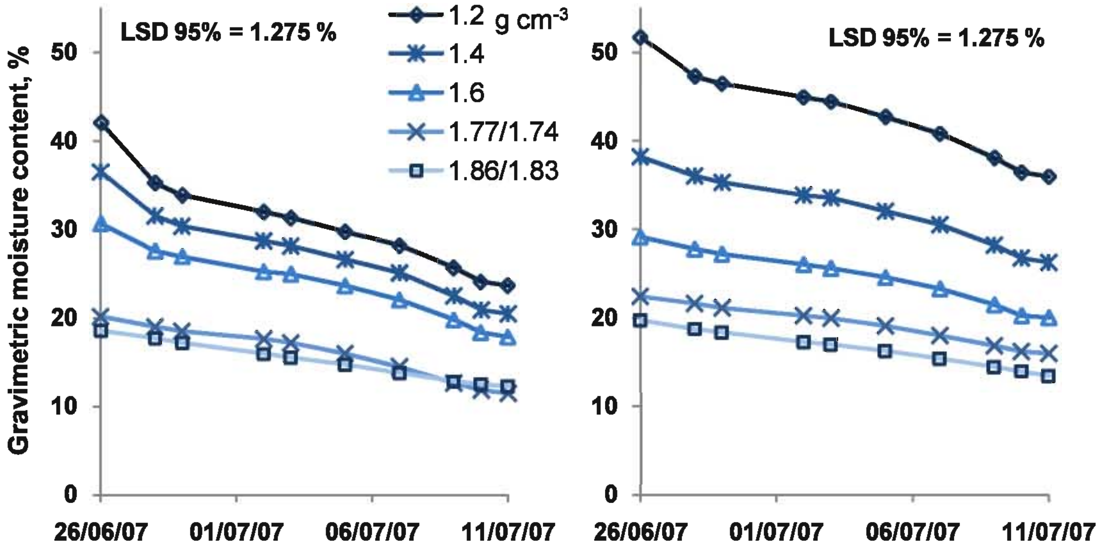

Figure 6.7 Mean soil gravimetric moisture content for 0-300 mm depth during 14 days drying for different bulk density treatments measured by sample weight loss. KL soil (left) had significantly lower moisture content for all densities throughout the drying period compared to OL soil (right).**

The low dry bulk density treatments had consistently higher initial moisture content but despite a faster decline in moisture the final moisture content after 14 days of drying was significantly** greater the lower the bulk density. Low bulk density soil has a higher level of voids (porosity) allowing for potentially higher moisture content. Larger pore size encouraged by a greater porosity will lead to more initial drainage and a faster evapotranspiration rate which encourages the faster drying rates in the lower bulk density soils. Particle size also affects the water holding capacity of a soil. The OL soil has a higher percentage of finer particles which reduces the average pore size. This reduces the amount of gravitational drainage and water particles are held more tightly within the soil matrix reducing the rate at which moisture is lost through evapotranspiration. This is illustrated by the total moisture weight loss from the treatment profiles during the drying period. The higher bulk density soils had a tendency to lose less moisture overall compared to lower bulk density soils and OL soil had significantly** less moisture weight loss compared to KL soil in four of the five density treatments (Figure 6.8). This indicates that different cricket soils will have different water holding capacities and drying rates which will also be influenced by soil bulk density.

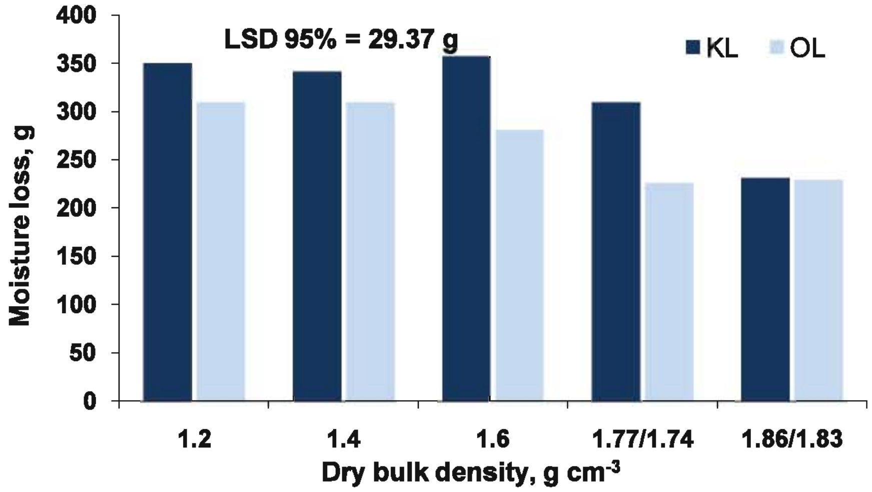

Figure 6.8 Total moisture loss from the 300 mm soil profile during 14 days drying. Significantly greater moisture loss occurred from KL soil than OL soil for treatment densities of 1.2, 1.4, 1.6 and 1.77/1.74 g cm^{-3}. Despite higher initial moisture content OL soil lost less in total than the KL soil.**

Moisture loss varied according to depth. This was significant** for the 0-50 mm depth only but occurred in all treatment densities. The 0-50 mm depth dried at a faster rate for all treatments compared to the other depths and was significantly drier after seven days drying for KL soil and 9 days drying for OL soil. The three other depths were not significantly different throughout the drying period. Figure 6.9 presents an example of this for 1.60 g cm^{-3} treatments for the KL and OL soils.

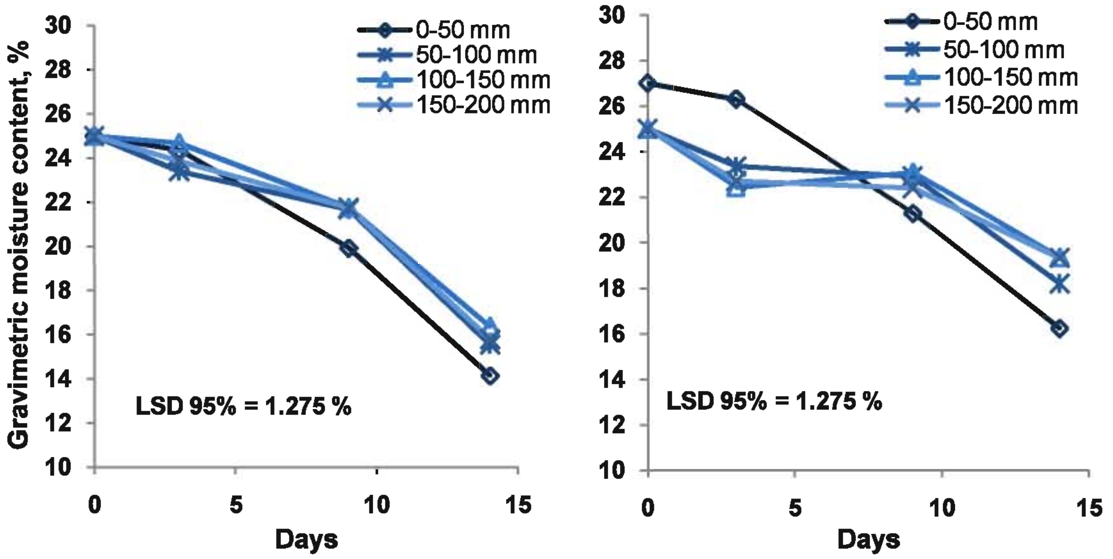

Figure 6.9 Moisture change during the 14 day drying period for different soil depths measured by oven dried samples. A comparison between KL (left) and OL (right) for the 1.60 g cm^{-3} treatment. Depth 0-50 mm is significantly different from the other depths throughout most of the drying period for OL soil and after 7 days for the KL soil. Final moisture content was significantly** lower for the 0-50 mm depth compared to the other depths for all treatments.**

Drying of the 0-50 mm is likely to be more crucial in terms of timing of pitch rolling and this was significantly** different between treatments and soil type (Figure 6.10).

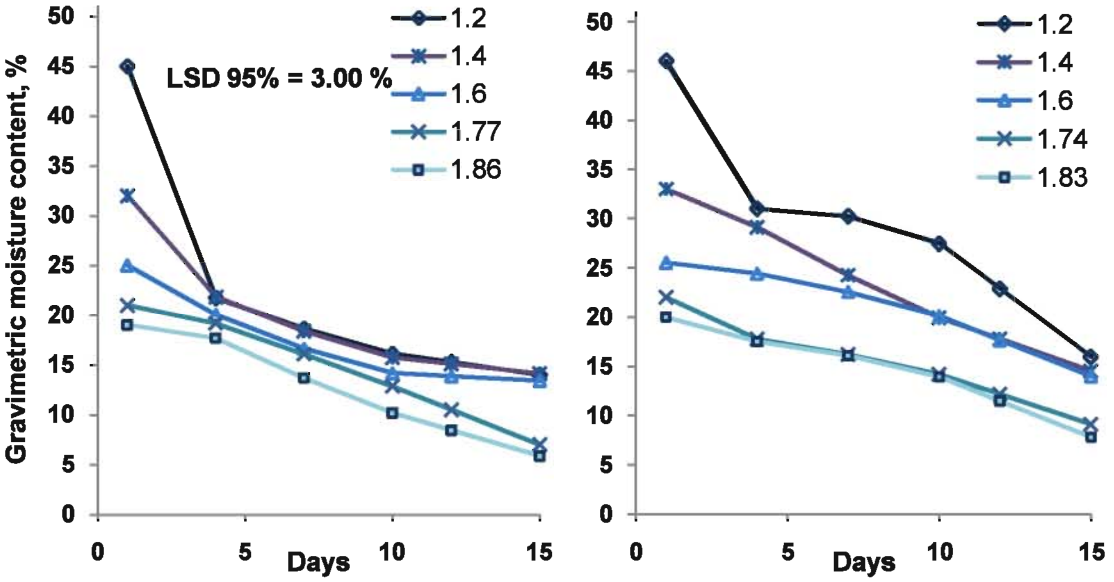

Figure 6.10 Gravimetric moisture content during the 14 day drying period for KL soil (left) and OL soil (right) for the depth 0-50 mm measured by oven dried samples. Moisture content was lower at all times for higher dry bulk density soils and for KL soil compared to OL soil in the 0-50 mm depth.

Similarly to the overall moisture content in the 0-300 mm depth the moisture content was lower for the higher bulk density soils and was also consistently lower for the KL soil compared to the OL soil.

Water release characteristics (WRC) were determined for a similar range of densities to the rooting experiment for comparison. Less restriction to expansion in the laboratory samples resulted in higher initial moisture contents affecting the comparison.

KL soil moisture contents for all bulk density treatments were at or below WRC field capacity within 48 hours and by six days moisture was at or below moisture contents determined for soils at a tension of 200 kPa, the point where most plants growth potential is reduced due to moisture stress (Taiz and Zeiger, 2002). The higher clay OL soil results were less consistent but for dry bulk densities of 1.40 and 1.60 g cm^{-3} it took four days to reach the 5 kPa tension moisture content (accepted field capacity tension) with dry bulk densities of 1.40 g cm^{-3} and above reaching 200kPa tension at nine days (Figure 6.11).

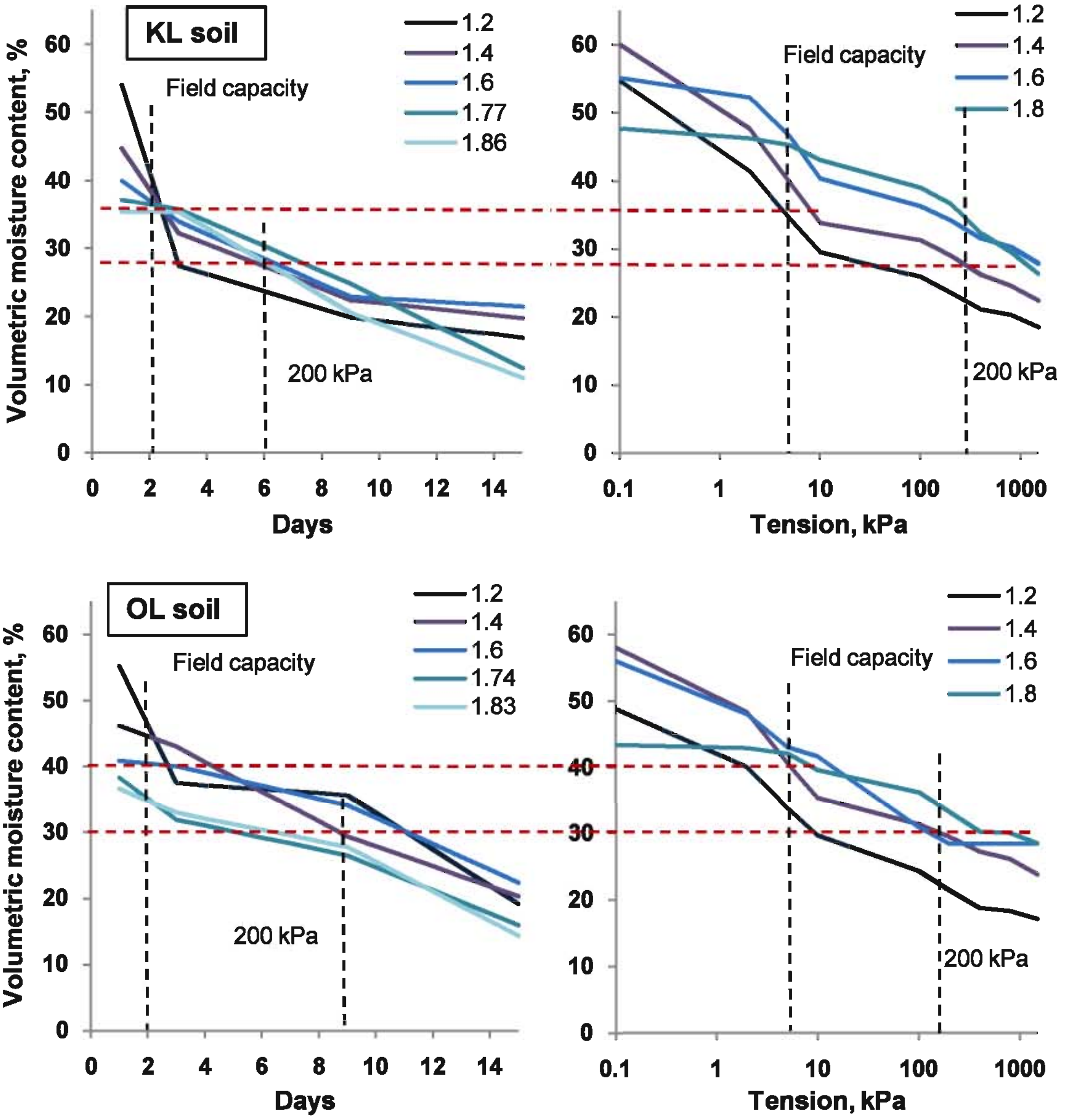

Figure 6.11 KL soil volumetric moisture content (top left) and WRC (top right) during the drying period. Field capacity achieved after two days and 200 kPa occurred at approximately six days for the 1.4 g cm^{-3} dry bulk density. OL soil volumetric moisture content (lower left) and WRC (lower right) field capacity achieved after two days for three of the treatments and 200 kPa moisture levels for the OL 1.4 g cm^{-3} dry bulk density was reached at 9 days.

The field capacity gravimetric moisture content for the KL soil was at approximately 22-24% for a 1.60 g cm^{-3} soil. This has already been determined as the optimum rolling moisture for a soil of this dry bulk density (Section 5.4.2). Rolling at this stage would therefore be appropriate. For the 1.60 g cm^{-3} OL soil to dry to 24% it took 4 days indicating the necessity of waiting for affective rolling conditions in the OL soil.

Treatments with grass roots were compared to those without and significantly** greater total loss in weight of moisture was determined for grass treatments (Figure 6.12).

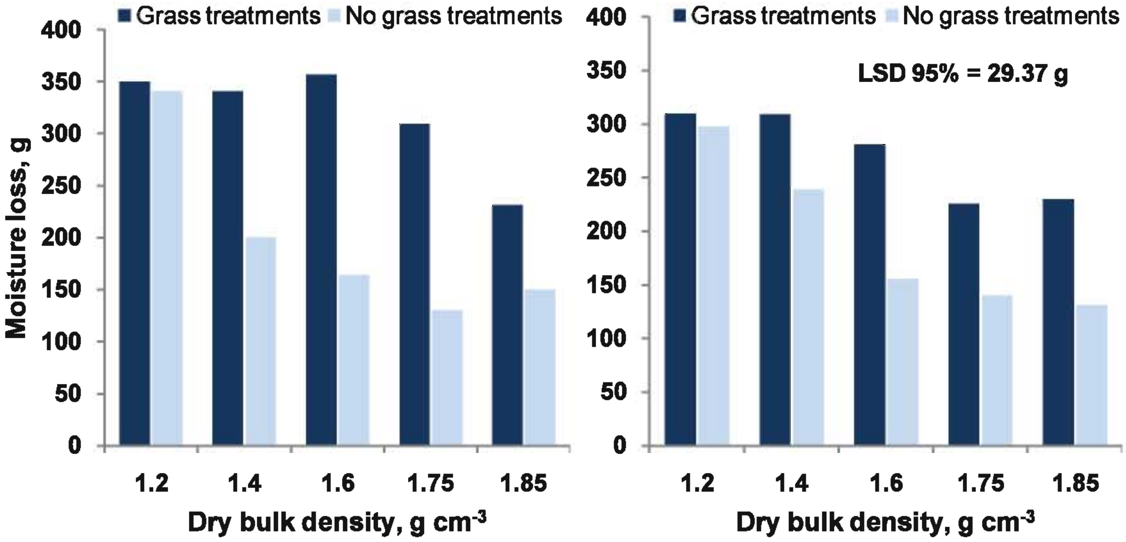

Figure 6.12 Comparison of moisture weight loss during the drying period between grass treatments and no grass treatments. KL soil (left) and OL soil (right) both indicated a significantly greater decline in weight of moisture for grass treatments compared to no grass treatments.**

Treatments with no grass also had lower initial moisture content that declined at a slower rate and were consistently drier throughout the drying period (Figure 6.13).

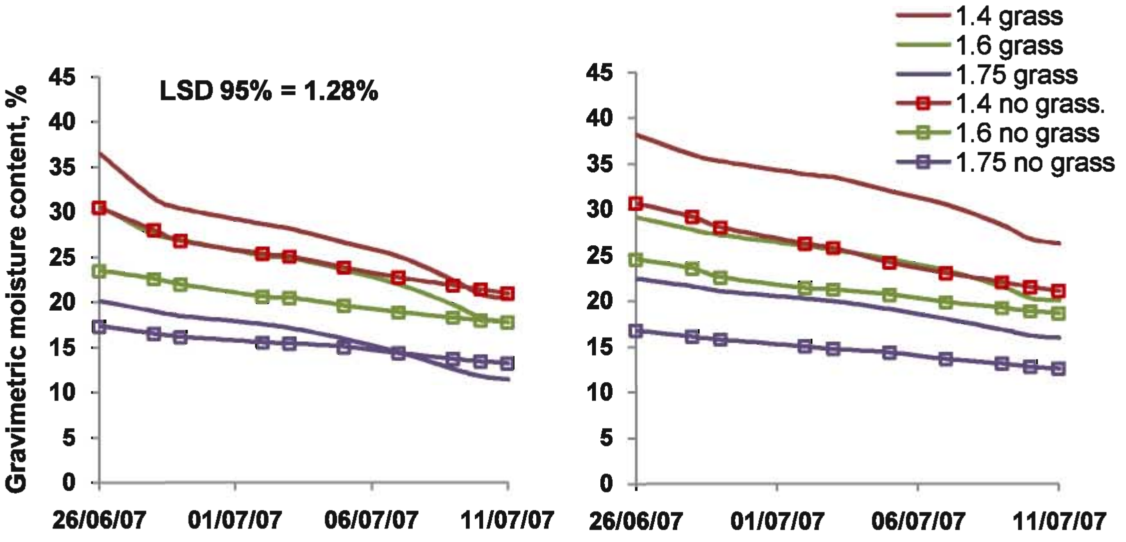

Figure 6.13 Comparison of moisture loss during the drying period between grass treatments and no grass treatments. KL soil (left) and OL soil (right) had greater initial moisture contents for the grass treatments however, due to a faster drying rate had final moisture contents that were not significantly different from the no grass treatments in seven of the ten treatments.

The lower initial moisture content of the no grass treatments was a result of the saturation process. 48 hours of immersion was undertaken to saturate the treatment samples which was not sufficient to achieve total saturation of the soil. Changes in soil structure resulting from grass roots could increase hydraulic conductivity as well as drainage. Whalley *et al* (2005) found that rooting into soil increased the amount of larger pores which would increase the speed of moisture movement. Dexter (1987) determined that growth of roots into compacted soil reduced porosity as root volume is accommodated by loss of porosity which would reduce initial moisture contents but this was not indicated by this experiment.

The generally faster decline in moisture content from the grass treatments would be expected to be as a result of plant transpiration and soil structural changes increasing the initial drainage. Evaporation driving capillary movement upwards through the soil to be evaporated at the soil surface removes moisture from the lower depths. The similar decline in moisture and final moisture contents between the grass and no grass treatments indicates that moisture removal by the grass through transpiration was low. The grass was cut to a length of 12 mm for the experimental drying period to match standard management practice (ECB, 2007) which will reduce grass transpiration because of the low leaf area.

6.5 Leaf tissue growth

Grass growth during the drying period was significantly** greater for KL soil which grew more dry matter than OL for four of the five treatments (Figure 6.14).

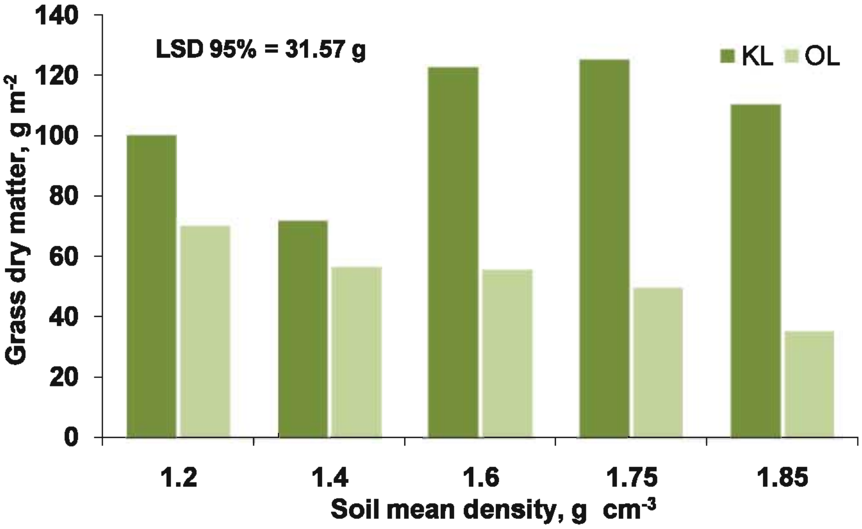

Figure 6.14 Total grass dry matter production during the drying period. KL soil produced significantly greater dry matter compared to OL soil in four of the five bulk density treatments.**

Growth did not significantly decline with an increase in dry bulk density in KL soil and only did so for OL soil when comparing 1.20 g cm^{-3} with 1.85 g cm^{-3} treatments. Grass leaf growth could indicate a link between greater total rootmass and greater moisture loss in the KL soil and the pattern of relative leaf tissue growth between treatments in Figure 6.14 has strong similarities with total rootmass in Figure 6.1. However the soil structure, mineral composition and bulk density will also affect the grass growth potential. Correlation of rootmass with moisture removed from the soil for all depths and treatments indicated a low statistical relationship (R^2 0.26). More work needs to be done to establish the relationship between grass root and leaf growth and moisture removal which could inform the process of even drying of the cricket pitch.

6.6 Summary of rooting experiment

Rootmass in the top 200 mm of the soil profile increased between 1.40 g cm^{-3} and 1.77 g cm^{-3} dry bulk density in KL soil and in OL soil the total rootmass was not significantly different at soil densities up to 1.83 g cm^{-3}. However increases in soil dry bulk density resulted in changes in rootmass distribution with an increase in root growth closer to the soil surface and a reduction in root depth. Reducing bulk density in the top 100 mm of the soil profile changed rootmass distribution. An increase in rootmass immediately below the 100 mm depth of reduced dry bulk density soil indicated a plant response to a change in bulk density was an initial increase in rootmass at that depth.

The KL and OL soils used for the experiment had different particle size distribution producing different soil physical conditions influencing root growth and drainage. The larger median particle size of the KL soil (D_{50} 45 µm compared to 11 µm for the OL soil) increased the potential for a greater number of larger pores offering less rooting impedance, greater drainage and gaseous exchange.

Winter growing conditions resulted in a visually more stressed grass growth through leaf yellowing and lower grass coverage (Batey & McKenzie, 2006) from the OL soil treatments compared to the KL soil and in particular the higher bulk density treatments; an indication of increased anaerobic conditions resulting from insufficient air-filled porosity (i.e >10% air filled porosity; Batey & McKenzie, 2006) caused by reduced drainage (Figure 6.15).

Figure 6.15 A range of root experiment treatments with KL (left) and OL (right) March 2007. OL soil showed visual signs of stressed grass growth compared to KL particularly with the higher dry bulk density treatments.

Soil dry bulk density influenced moisture removal with moisture in the lower bulk density soil declining at a faster rate although starting at higher initial moisture content. Rolling of the KL soil after two days of saturation would appear to be appropriate however the OL soil requires a longer drying period before rolling will be effective.

All treatments growing grass showed a greater moisture decline than no grass treatments although this was not consistently statistically significant. This indicates that roots increase moisture removal from the soil profile despite the length of grass being maintained at <12 mm. However this may also be as a result of a change in the soil structure resulting from grass roots aiding evaporation.

Assuming no further drainage occurred after 48 hours differences in drying between densities is a result of evapotranspiration. No differences in rootmass or grass leaf growth were determined up to 1.80 g cm^{-3} within soil type therefore reduced moisture losses due to increased dry bulk density are likely to be as a result of reduced evaporation. Cricket pitch drying will be dependent on initial densities which influence the initial moisture content. However as rolling increases bulk density the rate of drying could slow due to reduced evaporation.

Chapter 7. Cricket rolling simulator

To gain an improved understanding of the effect of rollers of different diameter, speed and load on soil movement and changes in dry bulk density within the profile, a cricket rolling simulator was designed and constructed specifically for the purposes of this research. The simulator enabled the testing of these roller parameters in different moisture conditions within the context of cricket pitch preparation as well as measuring the pressure distribution through the soil profile. The experiments undertaken aimed to inform the understanding of the influence of soil moisture, roller diameter, roller speed and grass roots on increases in soil dry bulk density following successive roller passes.

7.1 Hypotheses

Characterisation of soil behaviour when subjected to a dynamic load determined the effect of moisture on soil strength and stiffness (Chapter 4). Dynamic triaxial results indicated an increase in the load required to compact a soil as soil moisture reduces and as bulk density increases. The experimental work presented in previous sections enabled the formulation of working hypotheses for the rolling simulator experiments and form the basis for the data analysis:

1. Soil moisture content and rolling efficiency. Soil moisture content influences the plastic and elastic behaviour of soil and therefore the movement of soil under a roller will change according to soil moisture conditions. Soil moisture content will affect roller contact area and therefore contact pressure and pressure distribution through the soil profile which will influence the potential increase in bulk density.
2. Roller mass affects load which affects soil movement. An increase in roller mass will increase soil movement resulting in either a permanent or elastic change in soil dry bulk density.
3. Increase in dry bulk density diminishes with successive roller passes. Elastic movement resulting from successive dynamic loads will continue after permanent plastic deformation has reached a plateau for a particular set of soil physical parameters due to an increase in stiffness from compaction.

4. Roller speed does not change the rate of soil compaction or the maximum achievable dry bulk density in the speed range 0.3 km h^{-1} and 0.6 km h^{-1}. Roller speed was not found to influence dry bulk density change in previous field and soil characterisation experiments in the speed range currently applicable to cricket pitch rolling.
5. Roller diameter will change the pressure distribution through the soil profile as a result of a change in the soil contact arc length which will result in different levels of maximum compaction for a given roller mass. Contact pressure is determined by roller mass and the soil/roller contact area.
6. Grass roots influence soil strength characteristics and will increase the force required to compact soil. (It is necessary to investigate the influence of grass roots to qualify results from soil with no grass roots present).

7.2 Rolling simulator design and methodology[4]

The simulator consisted of a soil bin 3500 mm x 500 mm x 350 mm with a 600 mm x 250 mm glass viewing window in one side. A linear drive mechanism was used to propel rollers supported in a frame (Figure 7.1 and 7.2). A complete set of design drawings can be viewed in Appendix 8.

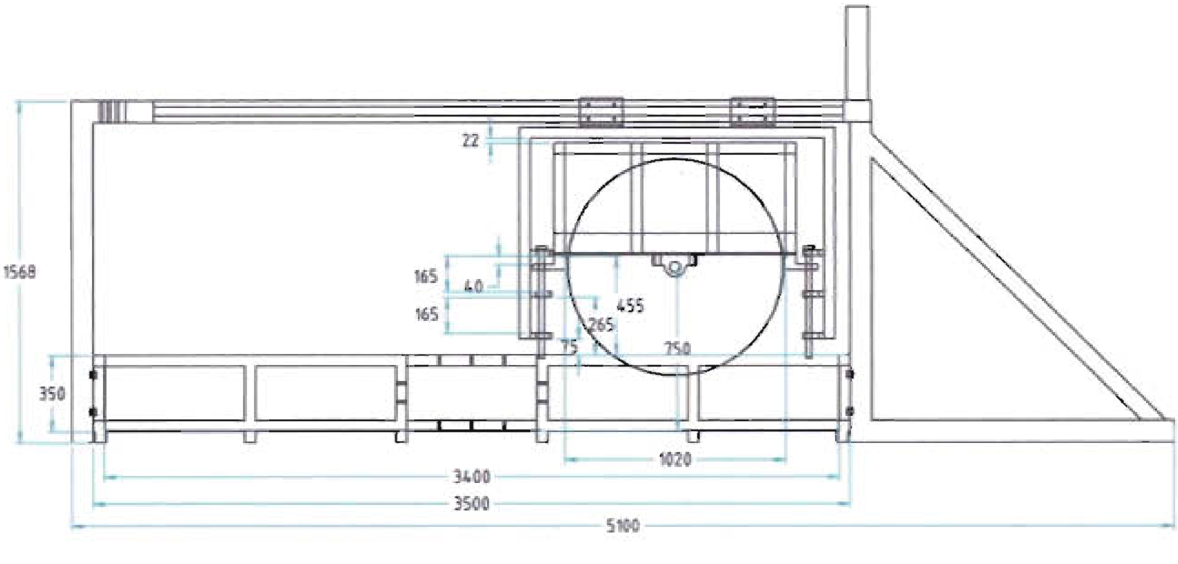

Figure 7.1 Cricket rolling simulator design. All dimensions are mm.

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[4] Methodology and preliminary results form the basis of a paper presented at the ISEA conference in Biarritz 2008 titled 'The Dynamic Compaction of Cricket Soils for Pitch Preparation' (Appendix 13).

Rollers 500 mm wide with diameters ranging from 200 mm to 1000 mm can be placed into a support frame that enables the roller to be towed in both directions within the soil bin. Additional weight was added to the frame as required to increase roller mass.

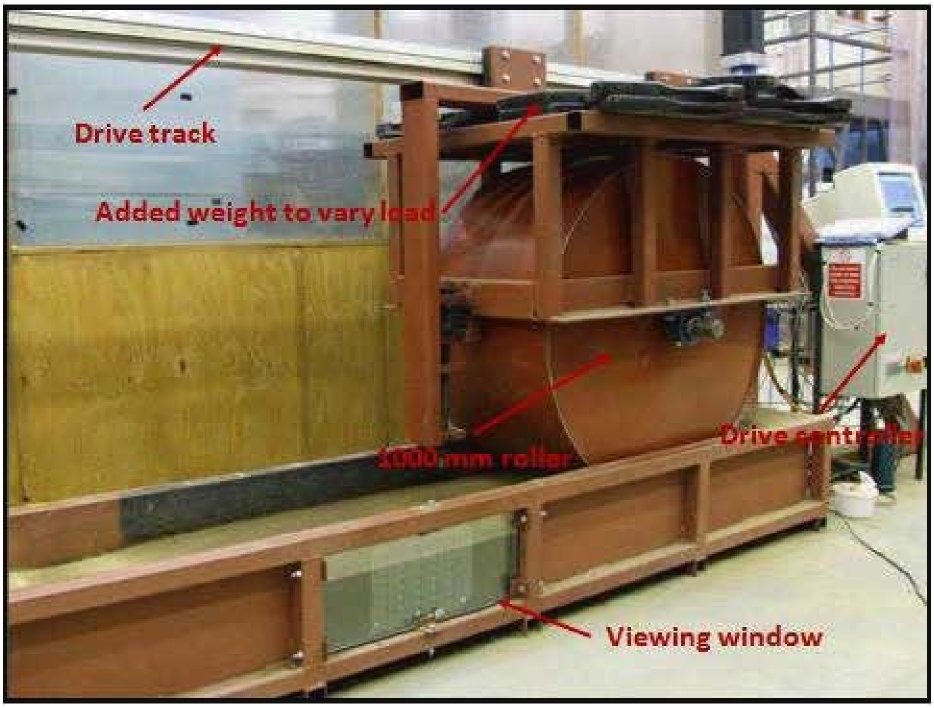

Figure 7.2 The cricket rolling simulator.

The fit of the roller within the bin is essential to the design to satisfy plane strain conditions, where strains in the longitudinal direction are assumed to be zero, therefore clearance between side wall and roller was maintained at less than 1 mm.

Drive was provided to a Hepco DLS4 linear guide bearing track (Hepco Slide Systems Ltd, Tiverton, UK) using a Baldor (Fort Smith, USA) BSM-C series brushless AC servo three phase motor and Baldor Flex+ Drive^{II} control system configured to provide variable speed from 20 mm s^{-1} to 1000 mm s^{-1} through a 10:1 gearbox (Wittenstein Ltd (Alpha Gearheads), Stoke, UK). The control system was operated by Baldor Workbench v.5 software, incorporating the Mint® programming language and code was written specifically for simulator operation (Appendix 9).

Calculation of the required track, motor and gearbox specifications were based on the force data measured during the soil bin rolling experiment described in Section 4.2.5. The required force to move a 625 kg roller at the maximum operating speed of 168 mm s^{-1} was only 300 N, well within the track rating of 1225 N. Because of

Newton's second law of motion (F = ma), to accelerate the roller from rest required considerably more force. Excessive acceleration could exceed the track load capacity so this was limited to a constant acceleration of 0.05 m s^{-2}. The track design configuration allowed for a maximum moment of force on the linear drive bearing of 280 Nm and roller load was configured not to exceed this in any phase of motion (acceleration, steady state or deceleration).

Simulator experiments

For all experiments the soil bin was filled to a depth of 250 mm with OL soil (as described in Section 4.1.1), with an initial dry bulk density of 1.20 g cm^{-3}. The soil was removed and replaced with fresh soil for each test.

Three separate experiments were conducted determining the effect of moisture, speed and roller diameter. Roller configuration and soil moisture content for each experiment are detailed in Table 7.1 (also Appendix 7).

Table 7.1 Roller configuration for simulator experiments.

No.	Experiment assessment	Soil moisture %	Diameter mm	Speed km h^{-1}	Grass	Roller mass kg m^{-1}
1	Moisture	16, 20, 25	600	0.3	No	260, 440, 840, 1250
2	Speed	20	600	0.3 / 0.6	No	260, 440, 840, 1250
3	Diameter	20	1000/600	0.3	No	260, 440, 840, 1250
4	Grass	25	600	0.3	Yes	260, 440, 840, 1250

Each roller load was used for six roller passes starting with the lowest mass and progressing through all four weights. The loads were selected to be equivalent to typical two drum cricket rollers (at 600 mm diameter) at masses of 500, 1000, 2000 and 3000 kg. The final roller load was used for eight roller passes giving a total of 26 passes for each test. Each test was replicated 3 times for each roller/moisture scenario.

Experiment 4 was conducted using a soil bin with grass growing in the soil profile. The grass had been sown six months earlier and grown outside to enable a comparison between results with grass and those without. Results for this test, which was conducted in the same way as previously described, were compared to the 25% moisture data from Experiment 1 (Figure 7.3).

Figure 7.3 Cricket rolling simulator with grass growing in the soil bin. The grass was initially grown outside from September 2007 until experimental work was undertaken in May 2008. Growth was maintained whilst inside using 'daylight' florescent tubes to ensure grass plant health whilst target experimental moisture content was achieved (25%). Note that the wooden panel was replaced with a glass window and that grass height was reduced to 5 mm during testing.

Experimental data acquisition

Pressure was measured within the soil profile for each pass of the roller using 18 mm diameter ceramic wheatstone resistive bridge sensor capsules (Applied Measurements Ltd, Aldermaston, UK). The sensors were mounted in steel tubing 25 mm x 35 mm and the sensor surface was covered with a rubber membrane to equalise pressure distribution and minimise damage. Sensors were calibrated using compressed air at a known gauge pressure. The sensors were buried at initial depths of 25, 50, 75 100 and 135 mm and the pressure data signal conditioning was provided by a Campbell 21X Micrologger logging at 10 Hz (Campbell Scientific, Loughborough, UK; data logger operating code is in Appendix 10; Figure 7.4).

Figure 7.4 Sensors with Campbell micrologger (left), sensors buried (centre) and calibration airline (right).

Changes in profile dry bulk density were calculated from vertical displacement of the surface measured after each roller pass. Soil movement within the bin was restricted to a length of 1.6 m by baffles constructed inside the bin to enable an accurate calculation of change in volume.

To analyse soil movement, plastic rod markers (5 mm diameter, 20 mm long) were placed into the soil during bin preparation adjacent to the side viewing window in a grid (Figure 7.5).

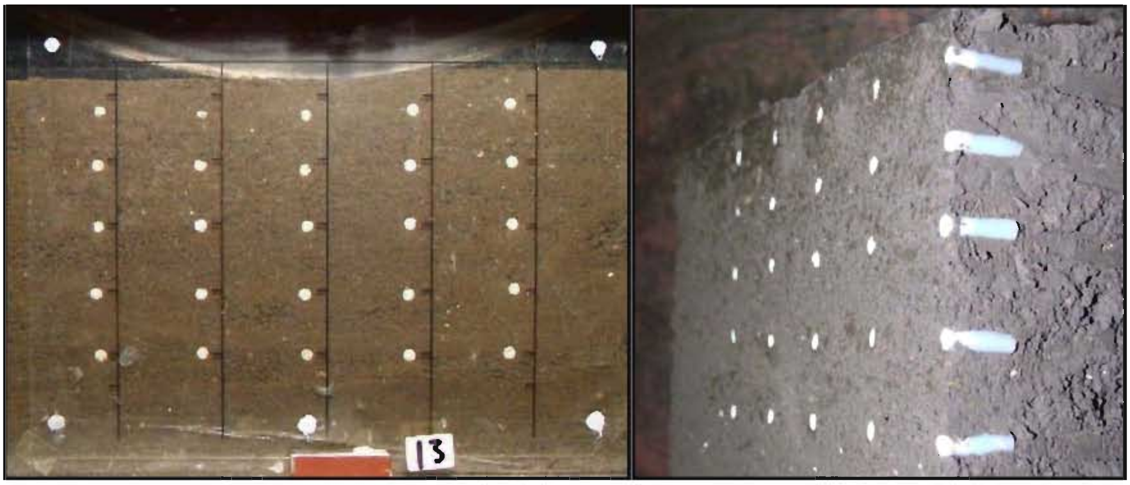

Figure 7.5 Rolling simulator side viewing window (left) showing grid of 25 markers embedded in OL soil. 5 mm diameter plastic markers, 20 mm long were inserted into the soil during preparation of the profile. Right hand picture was taken after a rolling experiment and shows no change in horizontal orientation of the marker after compaction despite vertical displacement.

The grid consisted of 25 markers in a 5 x 5 matrix with a column spacing of 50 mm and in rows at depths corresponding with the sensor starting depths (25, 50, 75 100 and 135 mm). Roller/soil contact arc was measured from video stills with the aid of ImageJ image processing and analysis software (available from:

http://rsb.info.nih.gov/ij/index.html). Movement of the markers was tracked for each roller pass using video footage captured with a Fujifilm Finepix S9600 camera. The resultant AVI format files were pre-processed in the image processing freeware Virtual Dub (www.virtualdub.com) to select the frames of interest and to compress the file using the Indeo 5.1 codec. Processed files were then analysed with VidiBin[5], image processing code written for Matlab (Mathworks, Cambridge, USA) (Figure 7.6).

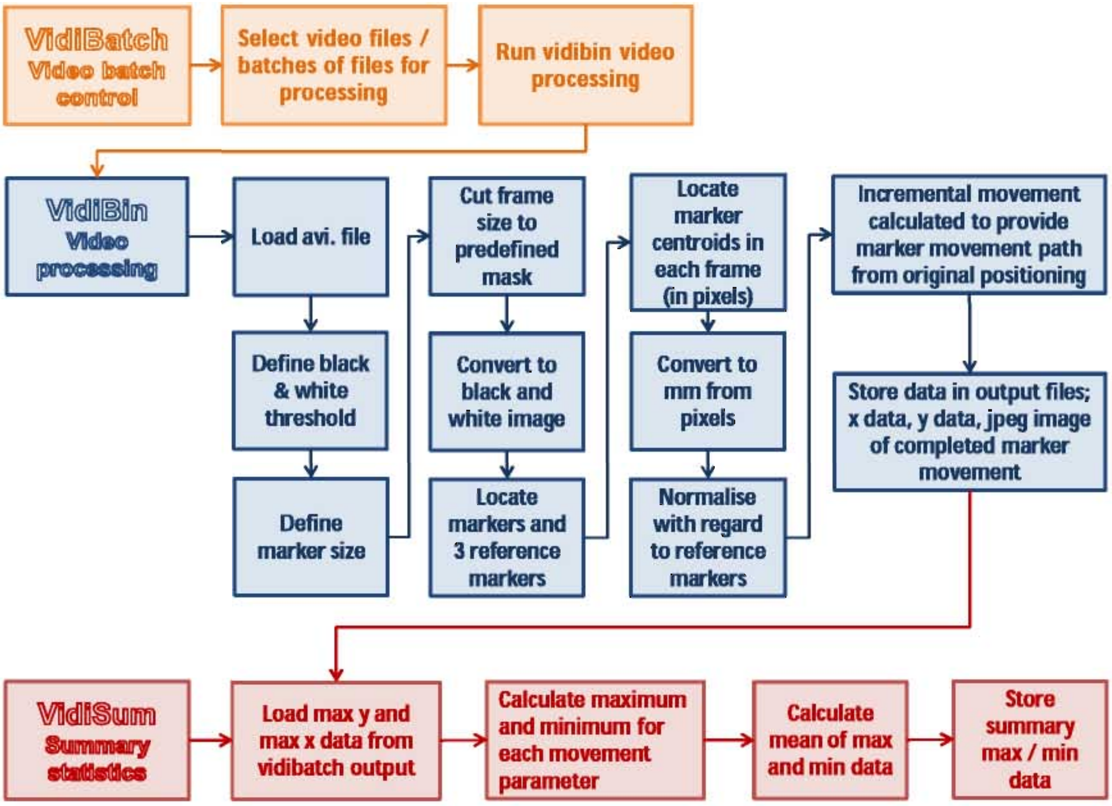

Figure 7.6 VidiBatch, VidiBin and VidiSum video processing code flow diagram of process procedure. VidiBatch is used to enable the batch processing of videos consecutively e.g. a complete series of videos from an experiment replicate. Vidibatch runs Vidibin for each video file to determine the position of each soil marker frame by frame and stores the data in terms of x (horizontal) and y (vertical) coordinates. VidiSum is used in a separate operation to assimilate the x and y data into the mean movement of the five replicated columns of markers for each of the five marker depths.

In brief the code determines the position of the soil markers relative to three reference markers placed on the outside of the window on a frame-by-frame basis. Camera movement relative to the soil is removed by tracking the absolute movement of the

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[5] The Matlab code VidiBin, VidiBatch and VidiSum were written by Dr Iain James, Cranfield University

reference markers. The output is an array of x (horizontal) and y (vertical) coordinates for each marker for each frame. Subsequent analysis using the VidiSum code determines four separate parameters that describe the movement of each marker (Figure 7.7).

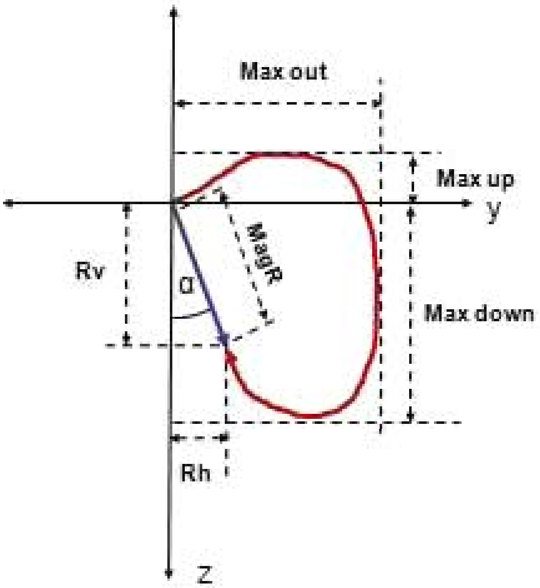

Figure 7.7 VidiSum calculated parameters from marker movement. The red line represents marker movement. Rh = residual horizontal movement and Rv = residual vertical movement.

A mean of each parameter for the five markers in each row was calculated to give a single value for each parameter at each depth. Replication for each of these measurements was three (three complete replicates for each experiment condition). The measurement results were subjected to a statistical analysis of variance to a significance level of $p < 0.05$.

7.3 Results

Results of the cricket rolling simulator experiments are presented in accordance with the hypotheses set out in Section 7.1.

7.3.1 The effect of moisture content and roller weight

Measurement of total change in the dry bulk density of the soil profile determined significant** differences between moisture content treatments. The 25% moisture content consistently indicated a greater dry bulk density than the 16% and 20% moisture and this was significant** for three of the four roller masses (260, 440, 840 and 1250 kg m^{-1}). The 20% moisture treatment indicated significantly greater dry bulk density than the 16% moisture for the two heaviest rollers (Figure 7.8).

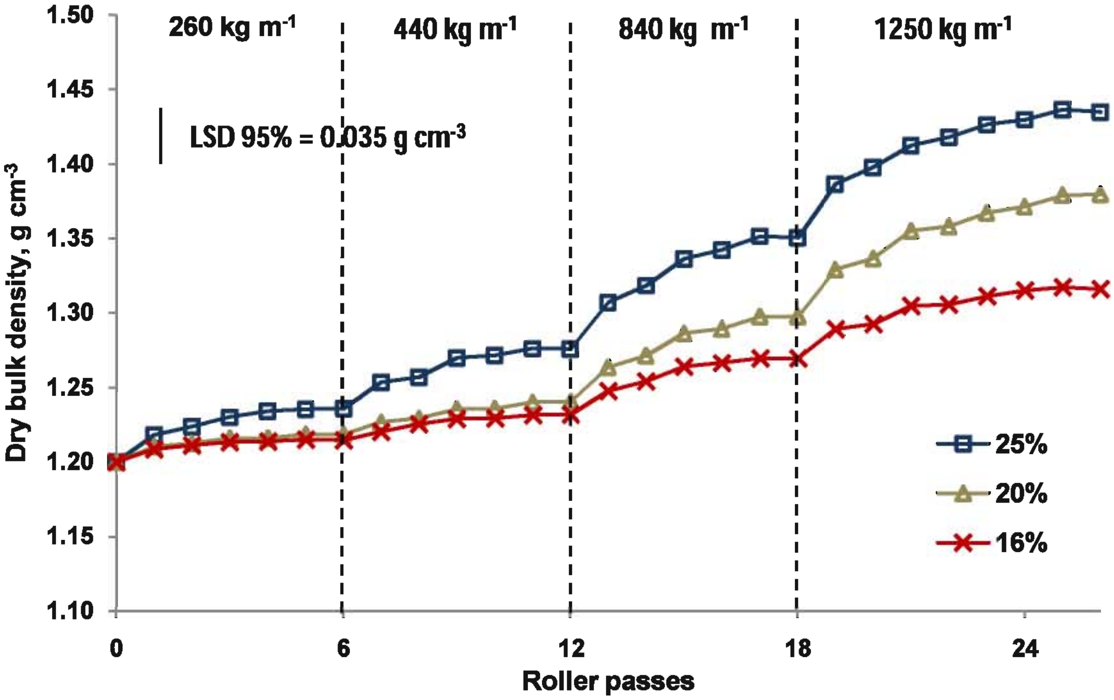

Figure 7.8 Soil profile change in dry bulk density from successive roller passes using four roller masses. Significantly greater densities were determined for higher soil moisture.**

An increase in soil moisture content reduces inter-particle friction and water suction and consequently the force required to increase soil bulk density. This results in greater increase in soil bulk density for a particular compactive load. At low densities the 25% moisture content soil has high levels of air voids which reduces with an increase in dry bulk density (i.e. a dry bulk density of 1.20 g cm^{-3} has 25% air voids and a dry bulk density of 1.60 g cm^{-3} has 0% air voids, at 25% moisture content). Moisture contents above 25% could be tolerated for compaction of lower bulk density soils however as soil voids reduce and become close to saturation further increases in soil bulk density would not be possible. Likewise as density increases in the 25% moisture content soil the potential to increase soil bulk density will become limited as soil voids approach saturation. The distribution of the change in dry bulk density and factors influencing this are analysed below.

7.3.1.1 Roller/soil contact area

Pressure on the soil by the roller is a result of force applied to an area of soil/roller contact that distributes the pressure into the soil. This will be affected by the mass, width and diameter of the roller and soil physical conditions. Video stills enabled the contact arc length of the roller to be measured and significant** differences were determined between moisture treatments and roller mass (Figure 7.9).

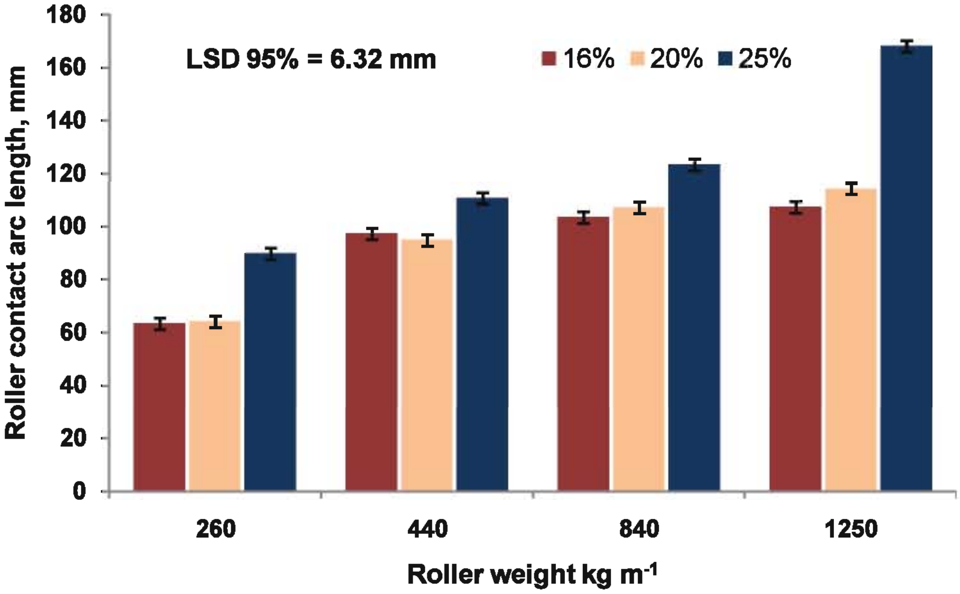

Figure 7.9 Roller contact arc length for four roller masses in the three moisture treatments. Contact width was significantly shorter for the 16% and 20% treatments compared to the 25% moisture. SE indicated by error bars.

Treatments with 16% and 20% moisture content were not significantly different from each other but both had significantly shorter contact arc length compared to the 25% moisture content treatment at all roller weights. An increase in roller mass resulted in an increase in contact length which was significantly** different among all roller weights for 25% moisture (Figure 7.10) but not consistently significant for the 16% and 20% moisture treatments.

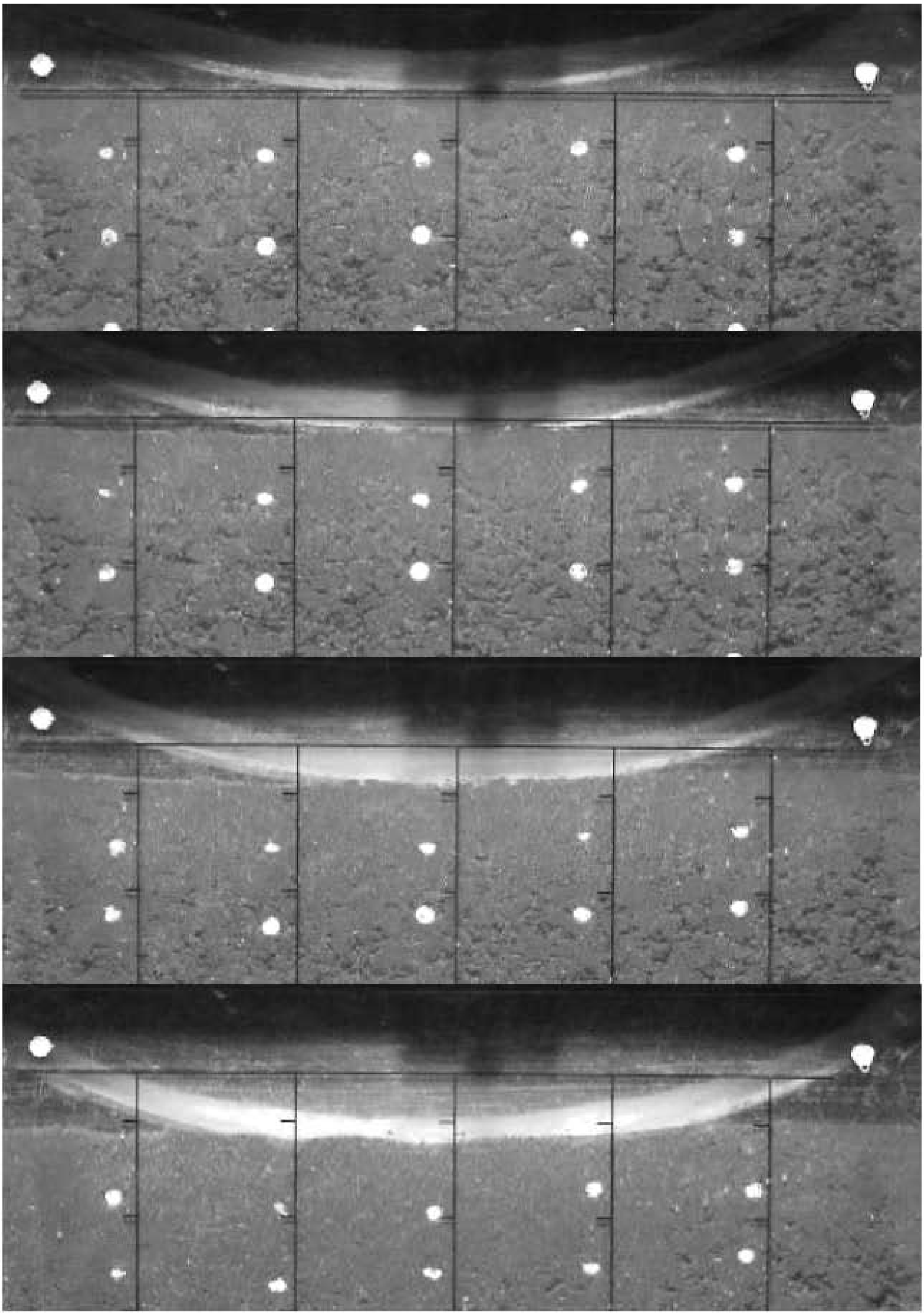

Figure 7.10 Roller/soil contact viewed through rolling simulator window. From top to bottom, 260, 440, 840 and 625 kg m^{-1} load on a 600 mm diameter roller on OL soil with a gravimetric moisture content of 25%. There is an Increase in contact arc with an increase in mass.

Arc length measurements were taken from rolling treatments for the first pass of an increased roller weight. Previous rolling had increased soil dry bulk density with repetitive roller passes therefore these comparisons are not consistently on soil of the same dry bulk density. Increase in moisture content will increase plasticity and reduce soil hardness (and stiffness) allowing for a greater sinkage of the roller into the soil.

Increase in dry bulk density as the soil is rolled progressively increases soil stiffness reducing plasticity and roller sinkage. Higher moisture content will result in greater sinkage at similar soil densities for all roller weights.

7.3.1.2 Pressure beneath the roller

Measurement of contact arc enabled the calculation of 'expected' surface pressure on the assumption that all of the rollers downward force is spread equally across the contact arc (Table 7.2). Sub surface sensors at 25 mm depth indicated higher observed pressures in all but one case.

Table 7.2 Expected roller contact pressure from roller contact arc and observed pressure at 25 mm beneath the soil surface (kPa) for three moisture treatments.

Roller mass	260 kg m^{-1}			440 kg m^{-1}			840 kg m^{-1}			1250 kg m^{-1}		
Treatment moisture	16%	20%	25%	16%	20%	25%	16%	20%	25%	16%	20%	25%
Contact arc length (mm)	64	64	108	98	95	111	104	108	124	108	115	169
Expected (kPa)	80	79	47	88	91	78	158	153	133	228	214	145
Observed at 25 mm	123	96	42	192	156	101	373	317	200	583	480	236

These results are in general agreement with Krick (1969), who showed distribution of pressure across the length of the contact was not even, and Way (1996) who determined a concentration of pressure immediately behind the central axle. Peak pressure was greater than the expected pressure measured from the contact width probably because of the reduced distribution of downward force at the edges of the contact arc resulting in greater contact pressure in the remaining contact arc length. In the case of the towed roller Krick, 1969 showed this to be forward of the roller axle (Figure 7.11). Surface pressure calculated from the contact arc is therefore not a good predictor of pressure beneath a roller and will also be influenced by soil conditions.

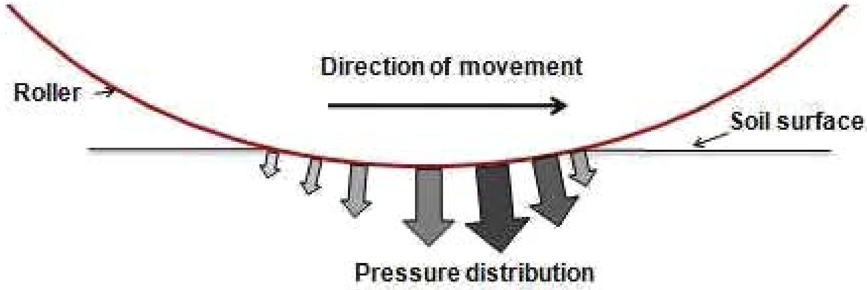

Figure 7.11 Diagrammatic representation of pressure distribution under a towed roller (based on Krick (1969) and experimental results). Reduced pressure at the edges of the soil contact arc results in a greater roller mass being supported by the roller arc forward of the roller axle therefore increasing soil contact pressure.

Dispersion of pressure through the soil will alter with different soil physical properties. Higher moisture content reduces inter-particle friction and increases soil compaction. Work done to move particles closer together reduces available energy and thus reduces pressure further from the source.

Pressures increased at greater depths with repetitive passes of the same load due to an increase in soil stiffness closest to the surface and a reduction in dissipated energy from soil compaction. Initial roller passes will therefore compact soil closer to the surface. With subsequent passes the pressure will increase to greater depths increasing the potential to compact the soil. Final dry bulk density will be determined by the amount of pressure applied to the soil and with reducing pressures with depth this will inevitably result in lower final densities as depth increases.

Theoretical pressure at a particular depth can be calculated from the uniform strip load equation in Chapter 1 (Equation1.9) which describes pressure distribution with depth beneath a load. However, having established that surface pressure calculated from Equation 1.9 from a soil/roller contact arc is unreliable it makes theoretical calculation using contact width potentially unrealistic. Equation 1.9 also does not allow for soil stiffness or elastic parameters and is therefore of little value when evaluating differences in pressure distribution relating to different soil physical parameters.

Pressure measurements for five depths and four roller weights are presented in Figure 7.12

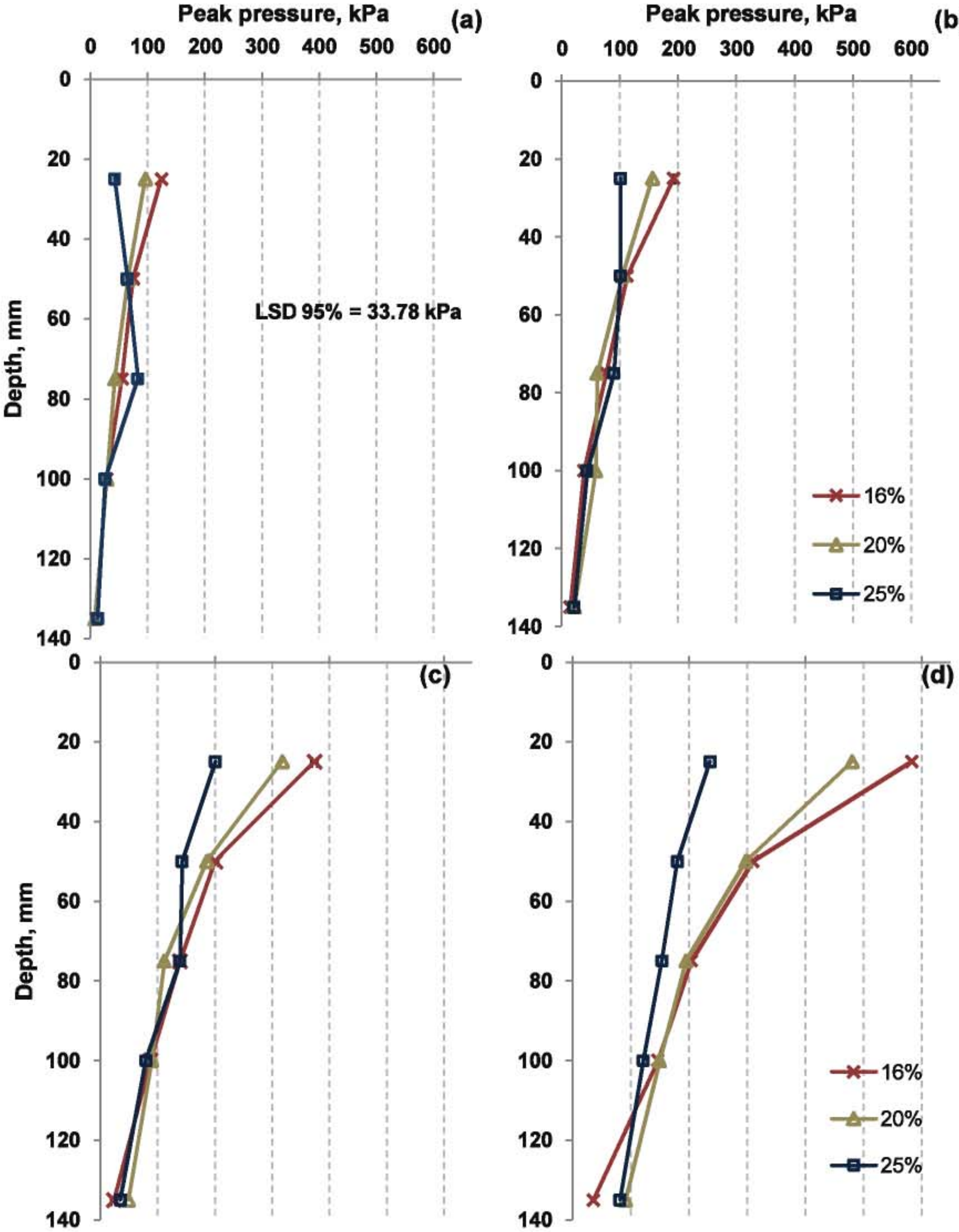

Figure 7.12 Measured peak pressure for three moisture contents at five depths beneath a 260 kg m^{-1} roller (a), 440 kg m^{-1} roller (b), 840 kg m^{-1} roller (c) and 1250 kg m^{-1} roller (d).

At the 25 mm depth significant** differences were determined in peak pressure between moisture treatments in all but one incidence (the difference between 16% and 20% for the 260 kg m^{-1} roller) with the higher moisture treatment being consistently at a lower pressure than a lower moisture content. This difference reduces with depth and is only significant** at 50 mm depth for the 840 kg m^{-1} and 1250 kg m^{-1} rollers and only between 25% moisture and the other two moisture content treatments. A significant** difference was only determined at 75 mm depth for the 1250 kg m^{-1} treatment between 25% moisture and the 16% and 18% moisture treatments. No significant differences in pressure were determined between moisture treatments below 75 mm.

Soil compaction requires energy to move soil particles closer together. Energy dissipation, as a result of work done, increases with greater levels of soil movement. Higher moisture content reduces soil strength and increases soil plasticity resulting in more work done moving soil particles closer together and therefore reduces pressure away from the initial contact area. However, higher soil moisture reduces the pressure required to move the soil and this reduced energy dissipation counters the reduction in pressure to lower depths.

Pressure is higher in dry soils due to the greater shear strength and stiffness reducing work done and energy dissipation on the soil. Pressure reduces more quickly in dry soils during compaction due to the greater energy (work done) required to move soil particles. Repetitive roller passes increase soil shear strength and therefore reduces plastic deformation (compaction), and therefore work done, this increase in shear strength and stiffness increases pressure deeper from the pressure source.

7.3.1.3 Duration of pressure

Pressure isobars resulting from an applied load indicate an initial increase in load duration with depth which is determined by load on the soil surface and soil physical parameters. Duration of pressure was determined to reduce with an increase in soil moisture indicating a steeper gradient of pressure isobar (Figure 7.13).

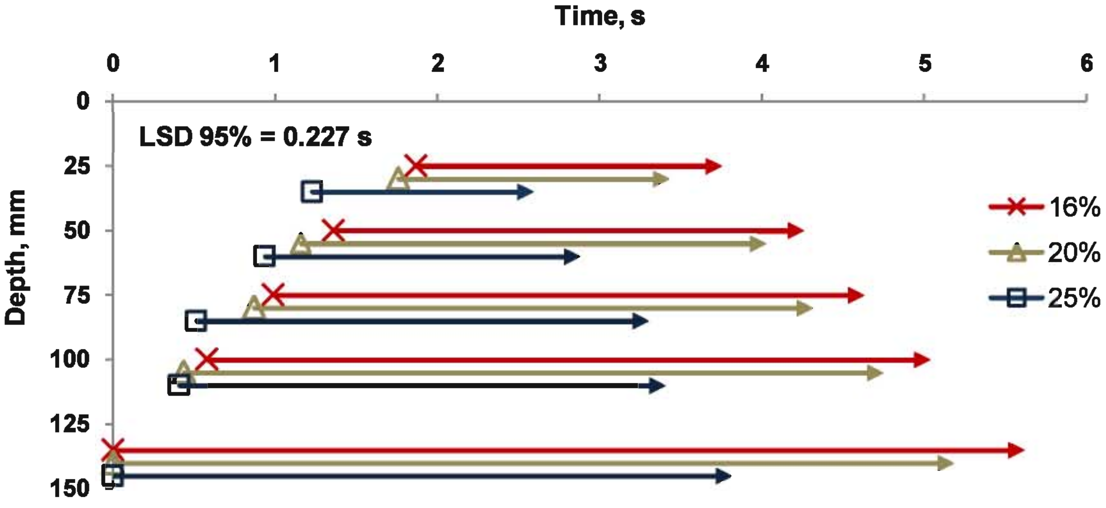

Figure 7.13 Duration of pressure for a 600 mm diameter roller for all roller weights. Significantly longer duration at all depths for the lower moisture content was determined.**

Pressure bulbs have been described by Koolen & Kuipers (1983) and others to be wider in harder soil. The drier soil treatments had this effect on pressure distribution and therefore the terms hard and soft could be synonymous with different moisture contents whereas roller mass and soil dry bulk density had no significant influence on the duration of pressure.

7.3.1.4 Soil movement and compaction

Soil displacement resulting from the roller load was measured using data from the soil markers. Soil mechanical properties have been shown to be influenced by soil moisture content with elastic and plastic strain components. Drier soil has been shown to have greater strength resulting in a lower increase in dry bulk density for a particular load. This was demonstrated in the soil marker movements which indicated that the 16% and 20% soil had a reduced permanent displacement compared to the 25% moisture soil. Figure 7.14 presents the results of the increase in soil dry bulk density as a result of permanent vertical displacement for the 15 mm depth at three moisture treatments and are combined with the maximum vertical marker movement.

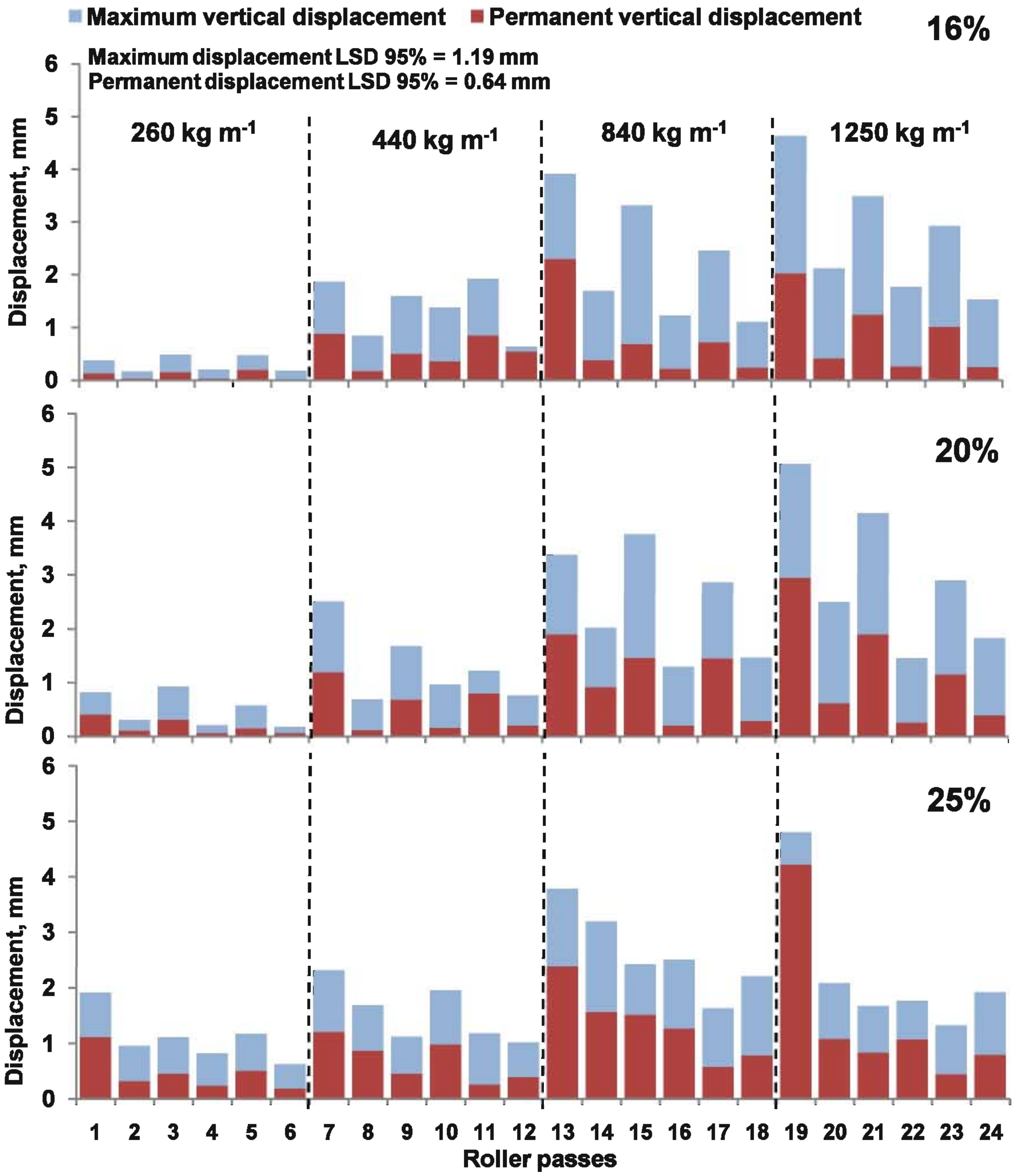

Figure 7.14 Maximum vertical displacement and permanent vertical displacement at three gravimetric moisture contents 15 mm depth.

Significantly** greater permanent displacement was determined for the 25% moisture for the 840 kg m^{-1} and the 1250 kg m^{-1} rollers. This also occurred at other depths but was not always statistically significant (Figure 7.15).

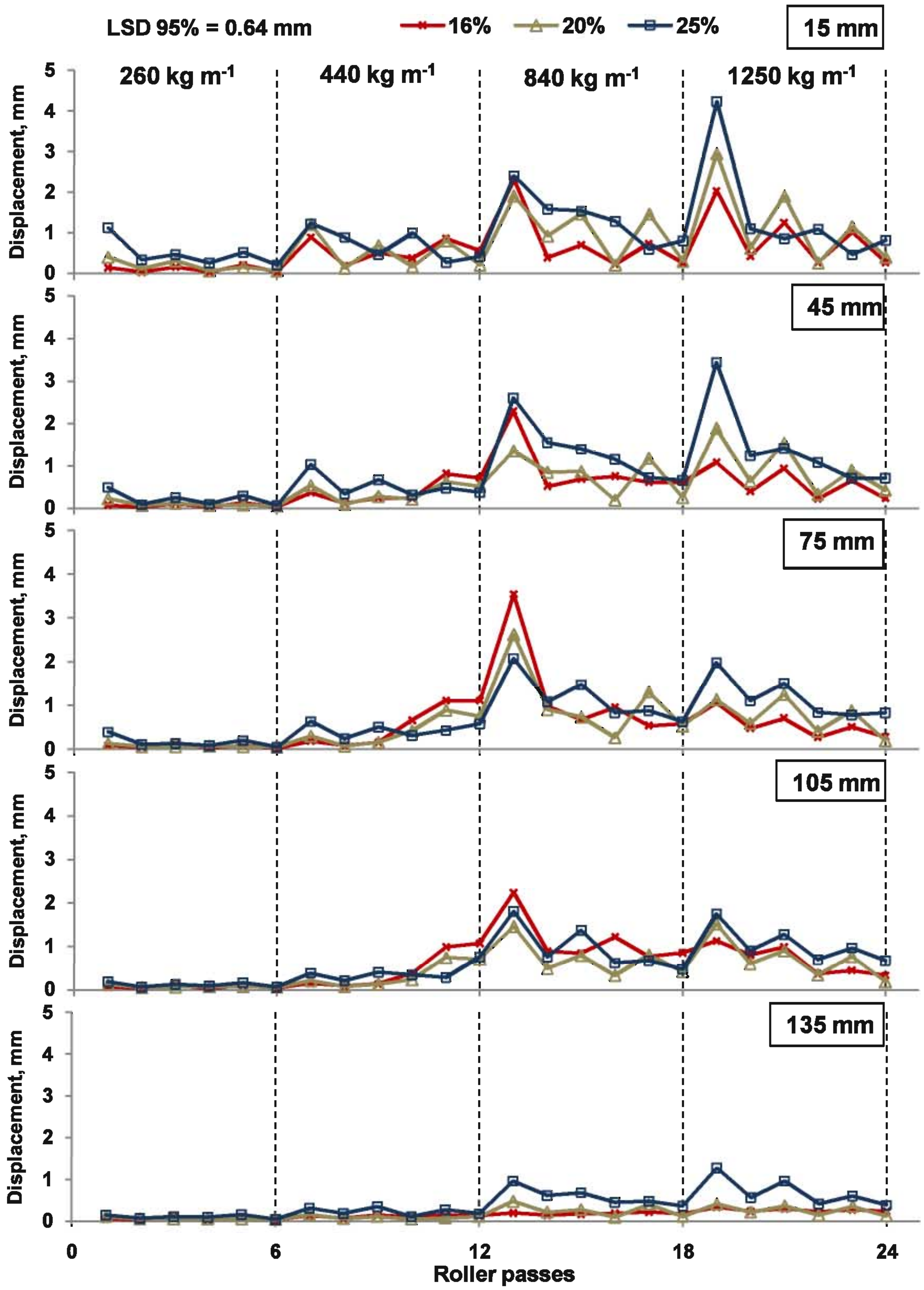

Figure 7.15 Soil marker residual vertical displacement (Rv) for five marker depths and 3 moisture treatments.

Marker displacement increased with load and declined with depth. Significant** differences occurred between moisture treatments however these were not consistent.

- No significant marker displacement was determined for the 260 kg m^{-1} roller for all depths.
- The 440 kg m^{-1} roller indicated some significant movement in the 15 mm marker but with limited movement at the other depths.
- The 840 kg m^{-1} and 1250 kg m^{-1} rollers produced significant** marker movement to 105 mm depth and to 135 mm with the 25% moisture treatment.
- The 25% moisture indicated significantly** greater movement than the 16% and 20% moisture soils for the first roller pass of the 1250 kg m^{-1} roller for four of the five depths.
- A significant** decline in movement occurred for all moisture contents after the initial pass with a roller mass for most of the depths and roller weights.

Soil dry bulk density measured from soil cores removed after all roller passes indicated significant differences in dry bulk density among moisture contents (Figure 7.16).

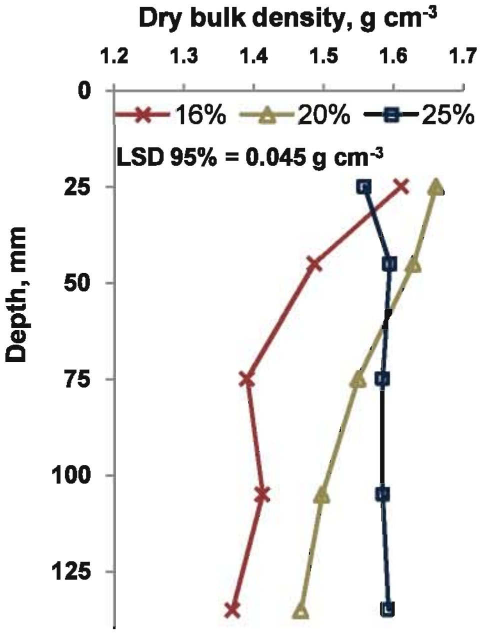

Figure 7.16 Dry bulk density in the soil profile after completion of 24 roller passes using the four roller weights.

Cumulative marker movement within the profile in conjunction with the final densities in Figure 7.16 enabled the dry bulk density change with successive roller passes to be derived for each marker depth range (Figure 7.17).

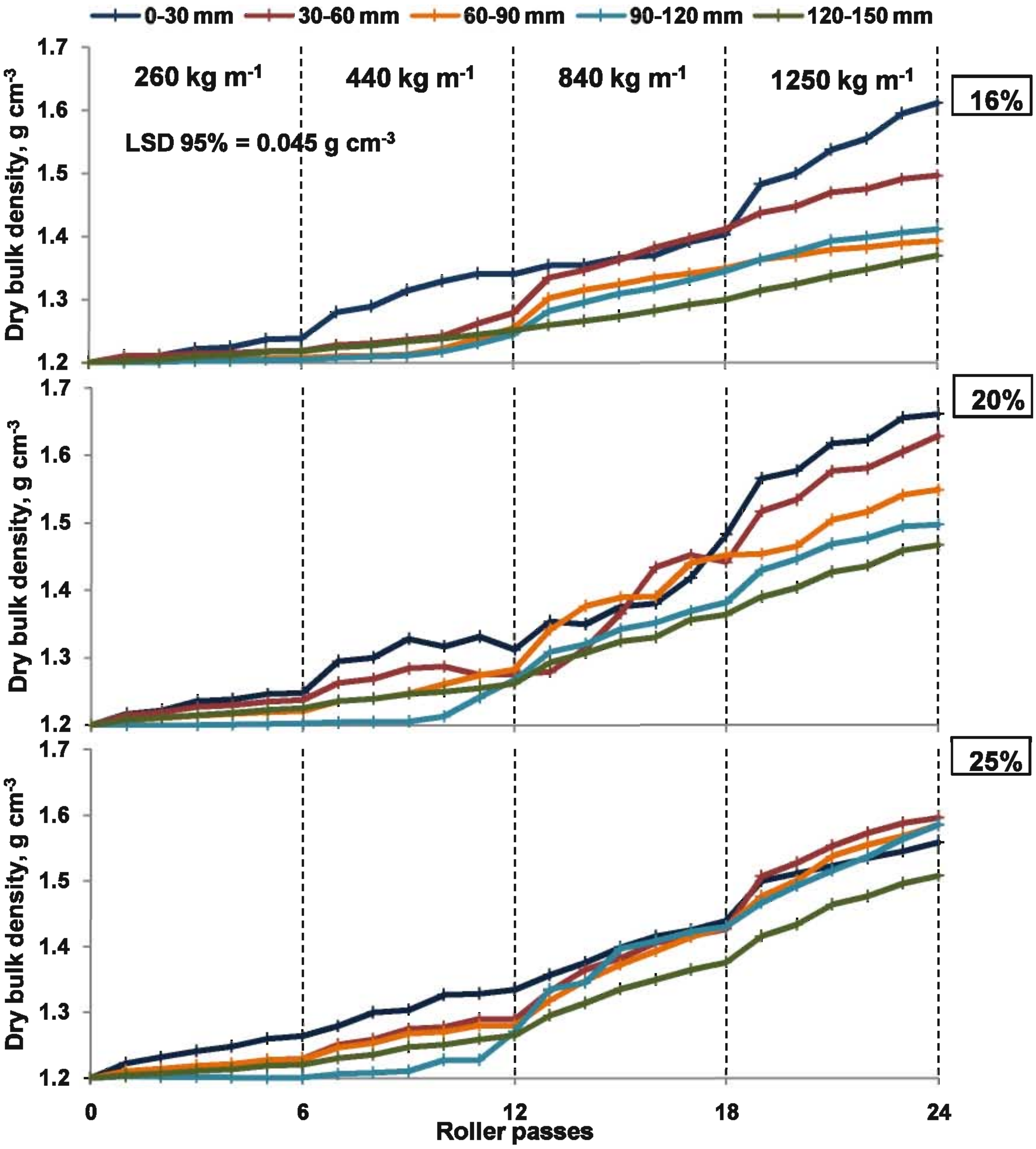

Figure 7.17 Increase in dry bulk density for successive roller passes based on Rv marker movement and final profile density.

The 16% moisture soil had a significantly lower final dry bulk density at all depths apart from 0-30 mm where it was significantly greater than 25%. The 25% soil was at approximately 3% air voids when at the final dry bulk density. Further increases in dry bulk density were likely to have been influenced by air filled porosity but results determined a more consistent density with depth and a significantly** greater dry bulk density than the 16% and 20% soil for depths below 75 mm.

No significant differences were determined between densities for moisture treatments for the 260 kg m^{-1} and 440 kg m^{-1} rollers.

The 25% moisture produced a greater overall profile dry bulk density at depths below 50 mm which could have implications for cricket pitch rolling. Rolling of drier soil may increase bulk density in the top 50 mm but result in a lower bulk density at lower depths. Initial rolling at higher moisture content up to 25% could enable bulk density at depths to at least 100 mm to be compacted to the rollers compactive potential and with subsequent drying the 0-50 mm depth could be compacted further.

Overall increase in dry bulk density in the 0-30 mm for an 840 kg m^{-1} roller was lower (1.45, 1.48 and 1.41 g cm^{-3} for the 16%, 20% and the 25% moisture respectively) than that achieved in the field experiments (1.61 g cm^{-3}) with the 920 kg m^{-1} roller for all moisture contents. The dry bulk density achieved with the 1250 kg m^{-1}roller was the same or greater than the density achieved in the field experiments for the 16% and 20% moisture treatments (1.61 and 1.65 g cm^{-3}). The optimum moisture content for a roller of this configuration has already been established as 22%. The 20% moisture was below this level and achieved 88% of Proctor maximum dry bulk density with the 840 kg m^{-1} roller and 98% of optimum with the 1250 kg m^{-1} roller. The 25% moisture was too high to achieve further increases in bulk density and was at zero air voids at the final dry bulk density of 1.58 g cm^{-3} which was 94% of optimum.

The 1250 kg m^{-1} roller has the compactive potential to increase dry bulk density closer to Proctor maximum when used in the correct soil moisture conditions (i.e. 1.65 g cm^{-3}; 20% gravimetric moisture content; 5% air voids). The 840 kg m^{-1} roller would need to be used at approximately 22% gravimetric moisture content to achieve its maximum compactive potential; this indicates the need for different optimum moistures for cricket pitch rolling depending on the roller mass.

7.3.1.5 Soil movement under a dynamic load

Tracing the movement of markers in the soil profile determined different movement characteristics between soil moisture for a particular roller weight. In addition to vertical strain movement discussed above higher moisture contents increased horizontal strain and also influenced upward strain. Figure 7.18 presents an example of VidiBin derived marker movement data for different moisture contents.

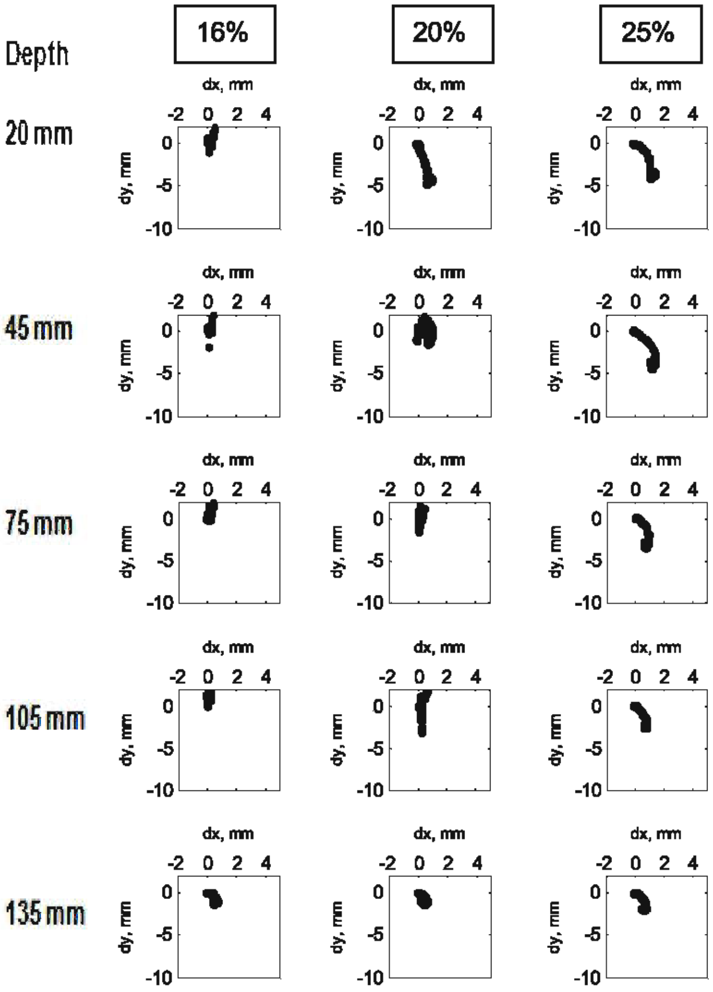

Figure 7.18 An example of marker movement for different moisture contents during rolling with a 840 kg m^{-1} roller mass on OL soil with densities ranging from 1.34 g cm^{-3} at the 20 mm depth to 1.25 g cm^{-3} at the 135 mm depth. Horizontal and vertical movement increase with an increase in moisture but reduce with an increase in depth. NB. Horizontal axis is magnified x2 c.f. the vertical axis.

VidiBin output derived an angle (α) being the angle between the vertical and the final location of a marker after a roller pass. All of the α measurements were determined to be in the direction of the roller movement resulting in the final marker location being forward of the initial position. This concurs with Wong (1967) who also determined that this occurred for a towed roller. Wong also determined that driven rollers would result in a soil particles being backward of the original position; this was due to the contact pressure distribution generating a greater pressure in the opposite direction to roller movement. This was not examined in this project.

From angle α and the magnitude of the vector R, describing the permanent marker displacement, a permanent horizontal movement was calculated. This measurement is combined with the maximum horizontal movement in Figure 7.19 for the 15 mm start depth marker.

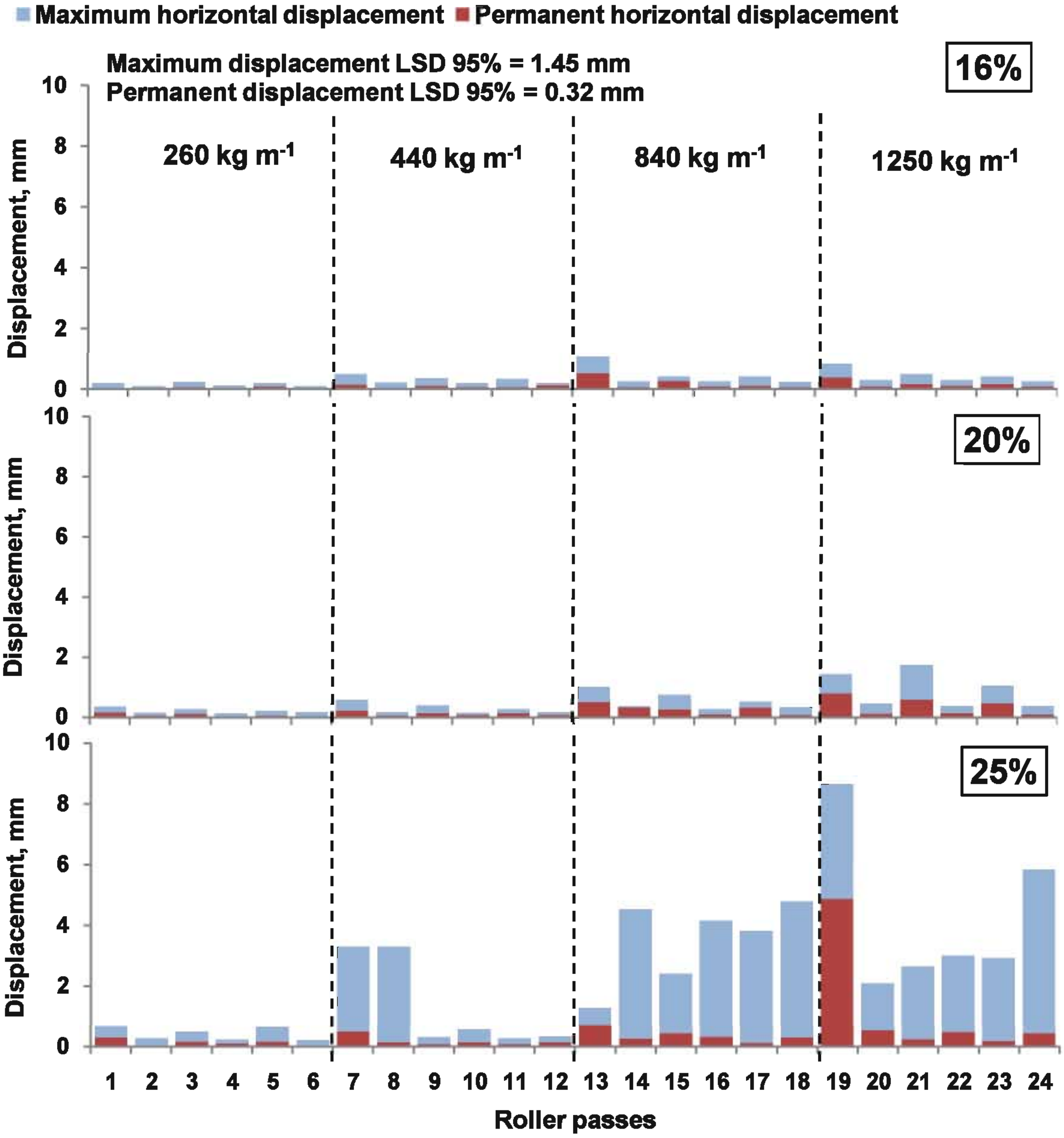

Figure 7.19 Maximum horizontal displacement and permanent horizontal displacement at 10-15 mm depth (marker depth reduces with increasing soil compaction i.e. roller passes) for all roller passes and three moisture contents. Significantly greater maximum displacement was determined for higher moisture content and heavier roller weights.**

No differences in horizontal displacement between 16% and 20% were determined but the increased horizontal movement from the 25% soil was statistically** significant.

Horizontal stress on roots could cause root damage however this stress reduces with depth and was not significantly different between all moisture treatments at 50-75 mm (Figure 7.20).

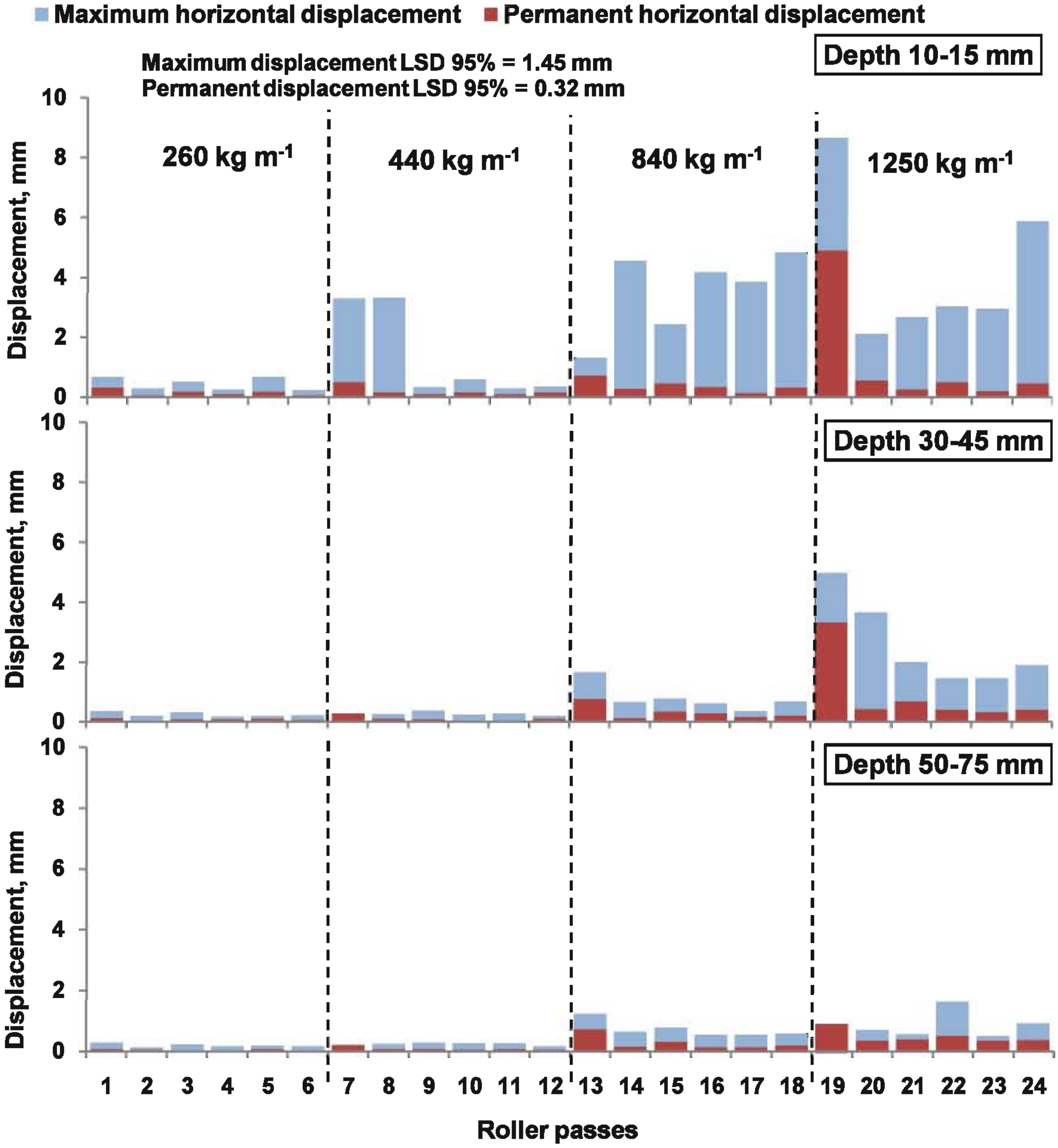

Figure 7.20 Maximum horizontal displacement and permanent horizontal displacement at three depth ranges (marker depth reduces with increasing soil compaction i.e. roller passes) for all roller passes for the 25% moisture content soil. Horizontal movement reduces with an increase in depth.

Significantly greater maximum horizontal displacement occurred for the 25% moisture compared to the 16% and 20% soil treatments. However, in only one roller pass (19) did this result in a significant increase in permanent displacement. Horizontal soil movement can potentially be the cause of damage to grass roots instigating ‘root breaks’ in the soil profile. Continuous horizontal movement with or without permanent displacement from successive roller passes could cause root damage to a depth of at least 30 mm. The amount of horizontal displacement increased with roller mass with statistically significant horizontal movement occurring for the 840 kg m^{-1} and 1250 kg m^{-1} rollers for the 25% moisture only. Heavier rollers and higher soil moisture content are likely to increase the amount of horizontal movement.

A significantly** lower upward movement was determined for the 25% soil for the 1250 kg m^{-1} roller resulting from a reduced downward resistance or greater horizontal movement in the higher moisture soil (Figure 7.21).

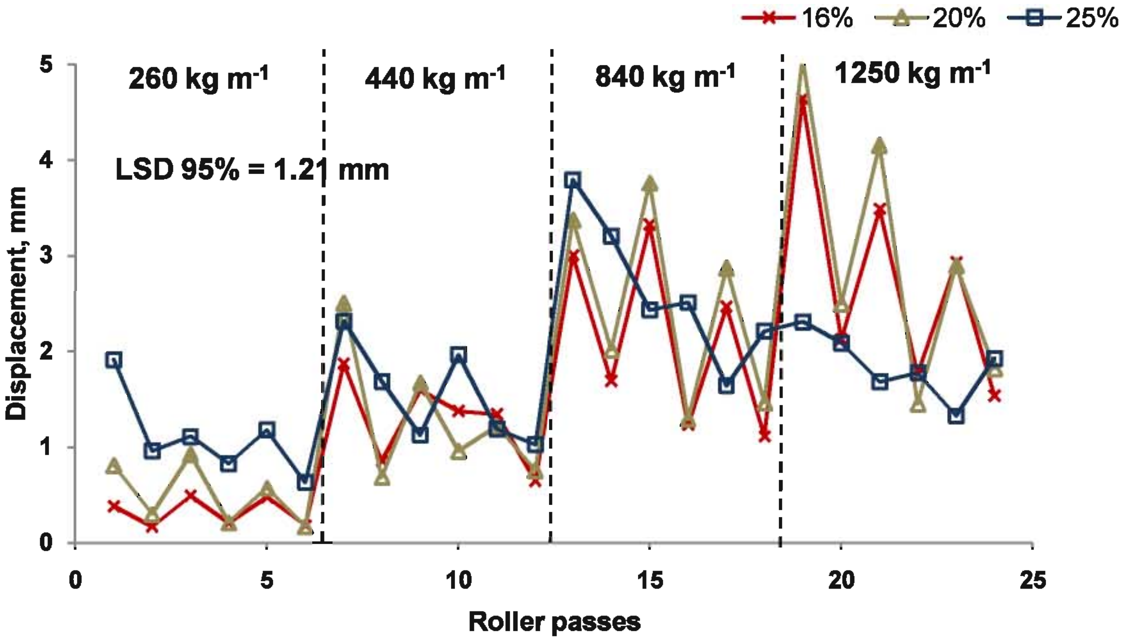

Figure 7.21 Soil upward displacement for the 15 mm depth. Note the significantly reduced upward displacement for the 25% moisture treatment for the 1250 kg m^{-1} roller mass.

7.3.1.6 Summary of the moisture experiment

Total increase in dry bulk density of the soil profile from a starting dry bulk density of 1.20 g cm^{-3} was greater with higher moisture compared to lower moisture content which was a result of an increase in density with depth for higher moisture but not a higher final dry bulk density in the 0-30 mm depth.

Higher moisture content increased roller contact arc length as a result of reduced soil strength. The resultant increase in roller contact area reduced surface pressure. However higher soil moisture reduces the force required to move and compact the soil which can result in greater compaction at lower depths despite the lower pressures. In the case of cricket soils, the increase in bulk density at depths to 100 mm could be beneficial to playability. Lower moisture content reduces contact area and results in a higher surface pressure which can result in a high bulk density on the surface of a pitch but with less bulk density at lower depths.

Pressure distribution through the soil declined with depth more rapidly for higher moisture contents due to the greater work done to compact soils with a smaller shear strength but was not significantly different below 50 mm depth for 260 and 440 kg m^{-1} rollers and 75 mm for 840 and 1250 kg m^{-1} rollers (600 mm diameter). Pressure duration was also longer for lower moisture content. However despite a lower pressure applied for a shorter duration, a higher moisture content soil increased dry bulk density to a higher level at depths lower than 50 mm due to the lower force required to compact soils which has previously been established. Further increase in dry bulk density for the 25% moisture soil was restricted at least in part by low air voids (2%).

A moisture content of 25% could be beneficial to cricket pitch preparation due to the increase in bulk density to a greater depth however horizontal movement of soil was determined to be significantly greater for the 25% moisture content soil to a depth of at least 30 mm which would result in an increase of stress on soil roots. Successive roller passes in these soil moisture conditions would increase the risk of root damage. These results are for a towed roller which leaves soil particles forward of their initial position. A driven roller has been shown by other work to leave soil particles behind the initial position. Cricket rollers often have a driven roller drum together with a towed roller drum and this combination will potentially influence the chance of root damage. However this was not examined in these experiments and should be considered for future study.

7.3.2 Load and roller passes

Soil moisture experiments also confirmed Hypothesis 2, roller mass affects soil movement and Hypothesis 3, increase in bulk density diminishes with successive roller passes. An increase in roller load consistently resulted in a significant** increase in soil dry bulk density with the first roller pass, with subsequent roller passes resulting in a diminishing increase in dry bulk density. Moisture was shown to influence the amount of dry bulk density increase for a roller weight; however roller weight was the most significant factor in increasing soil density. Increase in roller mass increased the pressure within the soil profile at all recorded depths therefore increasing the potential for compaction. Increase in pressure was to some extent reduced by an increase in contact area resulting from a greater mass and this was increased with greater moisture content. However the reduction in pressure was less than the overall gain in pressure resulting from the increase in roller mass.

Figure 7.22 shows the marker movement for the four roller weights at the three soil moisture contents. Soil dry bulk density increased as the roller mass was increased and in accordance with Figure 7.17 dry bulk densities were approximately 1.20, 1.25, 1.30 and 1.50 g cm^{-3} for the four roller masses 260, 440, 840 and 1250 kg m^{-1} respectively. Horizontal and vertical marker movement increased with an increase in roller weight however this reduced with depth.

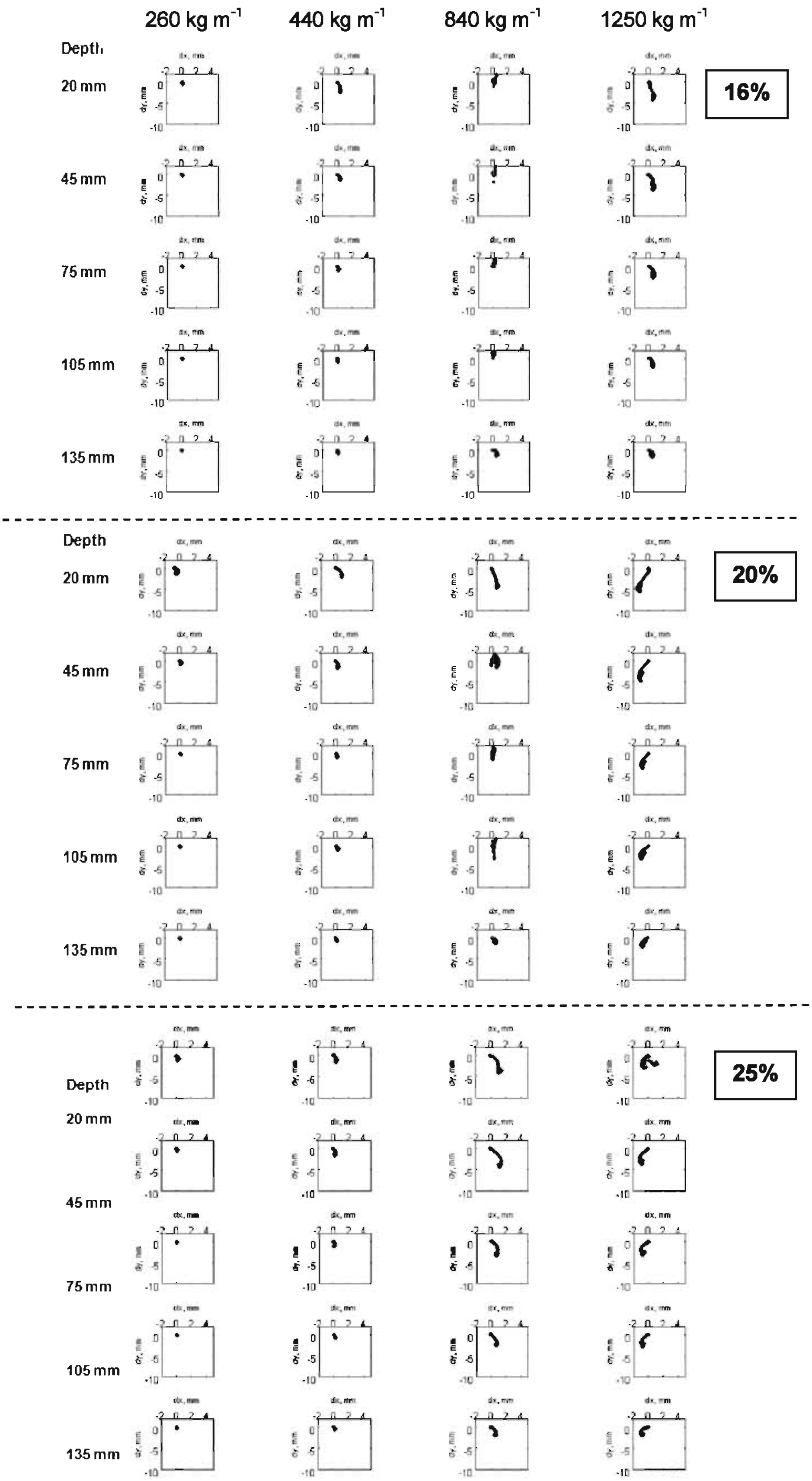

Figure 7.22 Marker movement for four roller weights and three moisture contents. NB. Horizontal axis is magnified x2 c.f. the vertical axis.

The percentage increase in dry bulk density from successive roller passes was significantly** affected by roller weight but not by soil moisture (Figure 7.23).

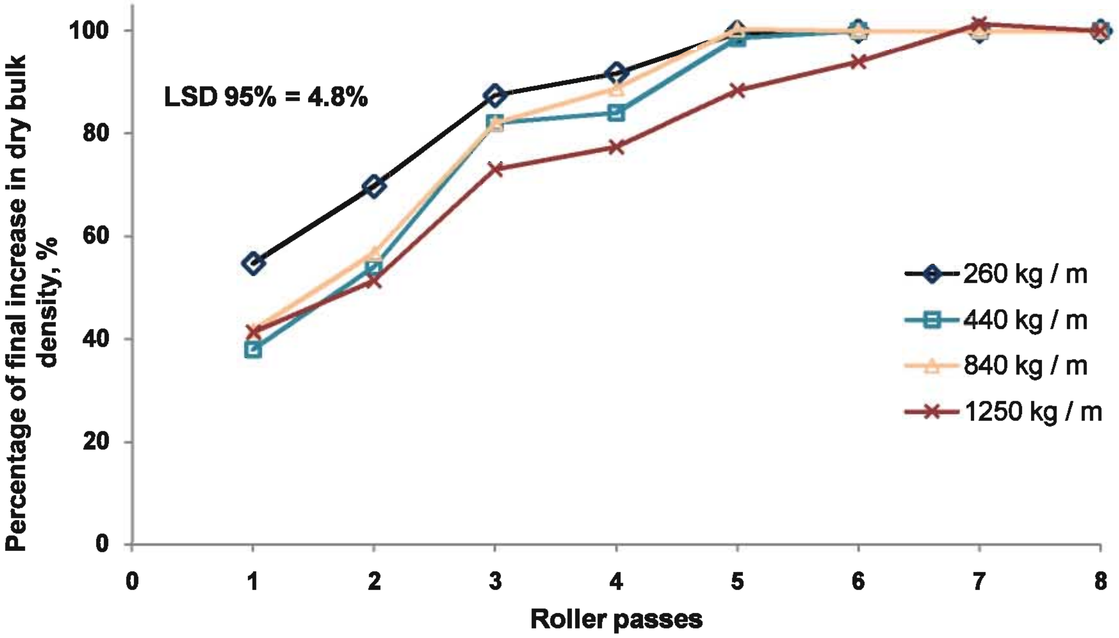

Figure 7.23 Passes to get to 100% of increase in dry bulk density. No significant difference for moisture. 100% achieved for all roller weights at 7 passes. Heavier roller has more gain and therefore achieves increase at a faster rate but with more roller passes.

Relatively small total increases in dry bulk density (0.02 g cm^{-3}) from the 260 kg m^{-1} roller were achieved significantly more with the first roller pass compared to the other rollers however this may have resulted from the initial profile surface conditions. The 1250 kg m^{-1} roller required more roller passes to achieve the final dry bulk density but the total gain in density was greater (0.07g cm^{-3}). Between 5 and 7 single roller passes were required to achieve 100% of a rollers increase in dry bulk density. Mean gain in dry bulk density per roller pass was 0.0073 g cm^{-3} however this was different for each roller mass and density achieved (0.0018, 0.0044, 0.0095 and 0.0089 g cm^{-3} for the roller masses 220, 440, 840 and 1250 kg m^{-1} respectively).

Mean increase in dry bulk density for a two drum roller based on these figures equates to 58%, 28%, 13% and 1.5% of final dry bulk density achieved for four successive passes. This is a greater rate of compaction than that suggested for compaction in agricultural (NSRI, 2001) which was though for lower density soils making greater gains in bulk density.

Increase in dry bulk density with repeated loads will increase soil stiffness and reduce plastic deformation. This also occurred for horizontal displacement and was more consistent and emphasised in the 25% moisture soil. Successive roller passes when soil has been compacted to the roller potential will result in a static level of elastic strain both vertically and horizontally but with no permanent strain benefit. No benefit to increasing pitch dry bulk density from rolling in these circumstances would accrue.

7.3.3 Roller speed.

Comparison of two roller speeds 0.3 km h^{-1} and 0.6 km h^{-1} for a 600 mm roller on a soil of 20% moisture content indicated no significant difference in overall profile dry bulk density or any differences at specific depths.

Duration of pressure was significantly** reduced with an increase in roller speed (Figure 7.24) however no significant difference was determined for peak pressure at all depths below the roller.

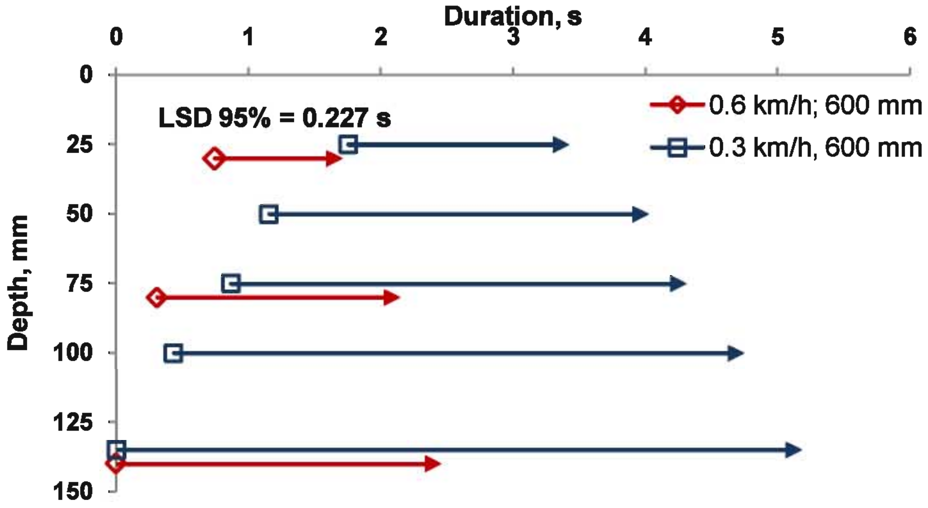

Figure 7.24 Duration of pressure for a 600 mm diameter roller for two roller speeds. Significantly longer duration at all depths for the 0.3 km h^{-1} was determined.**

Analysis of marker movement indicated no significant differences at all depths and although there was a tendency for the 0.6 km h^{-1} roller to create less horizontal marker movement which could reduce root damage this was also not statistically significant.

Hypotheses 4, roller speed does not change the rate of soil compaction, was confirmed with these results and compliments field trial and soil bin rolling experimental data.

7.3.4 Diameter

To inform Hypothesis 5, that roller diameter will change the pressure distribution through the soil profile leading to a difference in soil dry bulk density, two rollers with diameters of 600 mm and 1000 mm were compared to determine differences in density change and soil movement of a soil with 20% moisture content.

A significant** difference was determined for overall profile dry bulk density increase with the 600 mm diameter roller resulting in a greater density than the 1000 mm, however the difference was only significant for the 1250 kg m^{-1} roller (Figure 7.25).

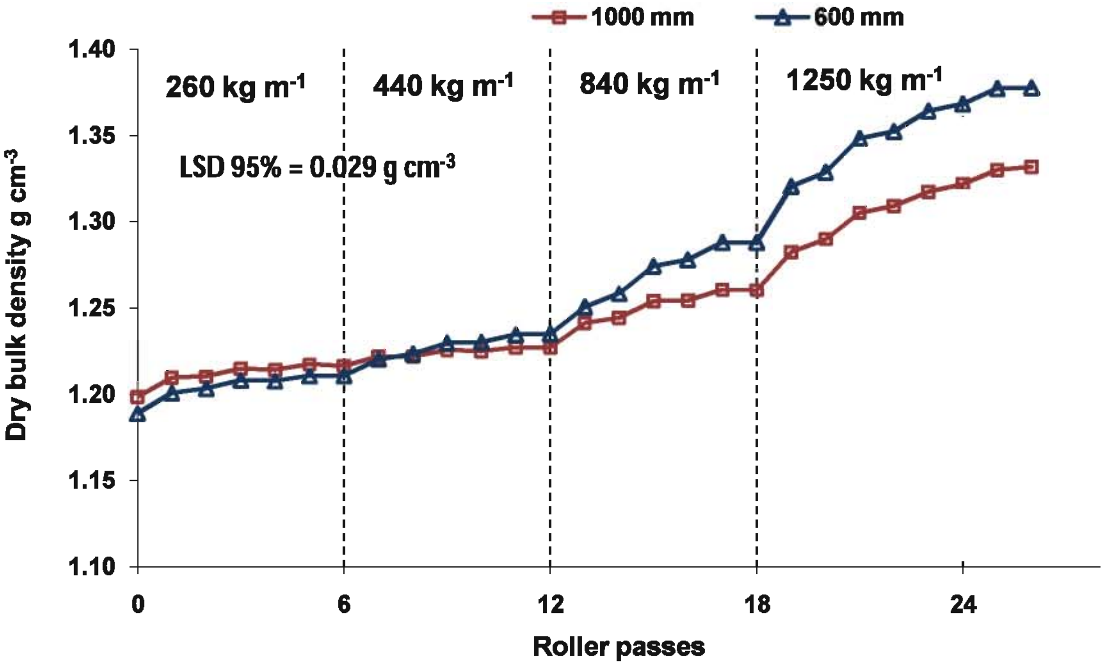

Figure 7.25 Soil profile dry bulk density change with consecutive roller passes for two roller diameters. Significantly greater density was determined for the 600 mm roller but only with the 1250 kg m^{-1} roller.**

7.3.4.1 Roller / soil contact

Roller contact arc length measurements determined a significant** difference between roller diameters for all roller weights (Figure 7.26).

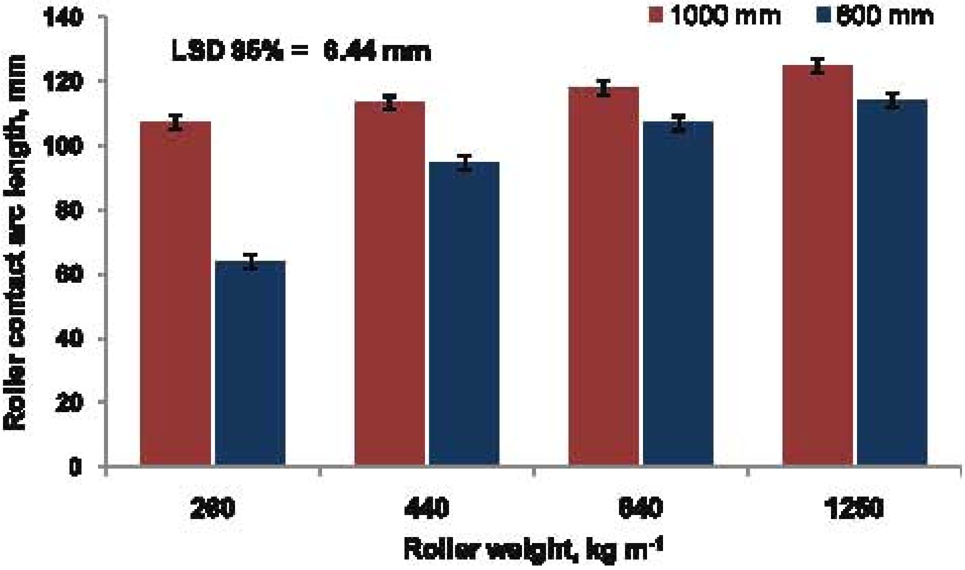

Figure 7.26 Roller contact width for two roller diameters at different roller weights.

The 1000 mm diameter roller had no significant change in roller arc length for different roller weights or for changes in soil dry bulk density. The soil density increased with each roller weight which increased soil shear strength. This increase in shear strength was enough to support the additional force from an increased roller weight.

At low masses (260 kg m^{-1}) difference in pitch indentation is unlikely due to 56% less contact arc length of the 600 mm diameter roller. A 1000 mm diameter roller is likely to have less indentation in the pitch than a 600 mm roller as roller weight increases due to the increasingly similar contact arc length (Figure 7.27) although the greater sinkage could be as a result of increased compaction.

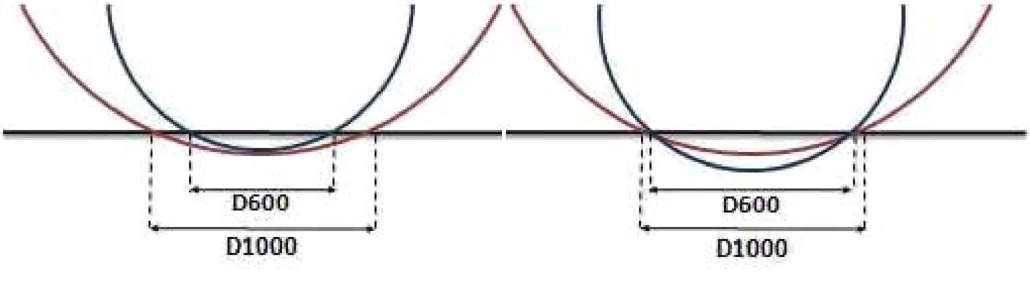

Figure 7.27 Diagrammatic representation of roller sinkage for two roller diameters. For a 260 kg m^{-1} roller (left) a 600 mm diameter roller (D600) had a 56% shorter contact arc which resulted in a potentially similar sinkage depth to the 1000 mm roller (D1000). As roller mass increased the difference between contact length between the two roller diameters reduced which resulted from an increase in the depth of roller sinkage for the 600 mm diameter roller (right).

Contact arc will determine the potential surface pressure and subsequent pressure at depth. Increased indentation by the 600 mm roller may be an indication of an increase in bulk density but this will depend on soil moisture content and initial bulk density.

7.3.4.2 Pressure distribution

A comparison of expected surface pressure for two roller diameters of 600 mm and 1000 mm was calculated using contact arc length rolling a soil with 20% gravimetric moisture content. These results were compared to recorded pressure (Table 7.3).

Table 7.3 Expected roller contact pressure from roller contact arc and observed pressure at 25 mm beneath the soil surface (kPa) for two roller speeds and two roller diameters.

	260 kg m^{-1}		440 kg m^{-1}		840 kg m^{-1}		1250 kg m^{-1}	
Roller diameter, mm	600	1000	600	1000	600	1000	600	1000
Contact arc length (mm)	64	116	95	122	108	118	115	125
Expected pressure (kPa)	80	44	91	76	152	140	213	196
Observed at 25 mm (kPa)	96	77	156	105	317	215	482	367

Recorded pressure was consistently greater than expected (as measured from surface contact arc length) for both roller diameters. Pressure at 25 mm was significantly** greater for the 600 mm roller for three of the four rollers (not the 260 kg m^{-1}) (Figure 7.28).

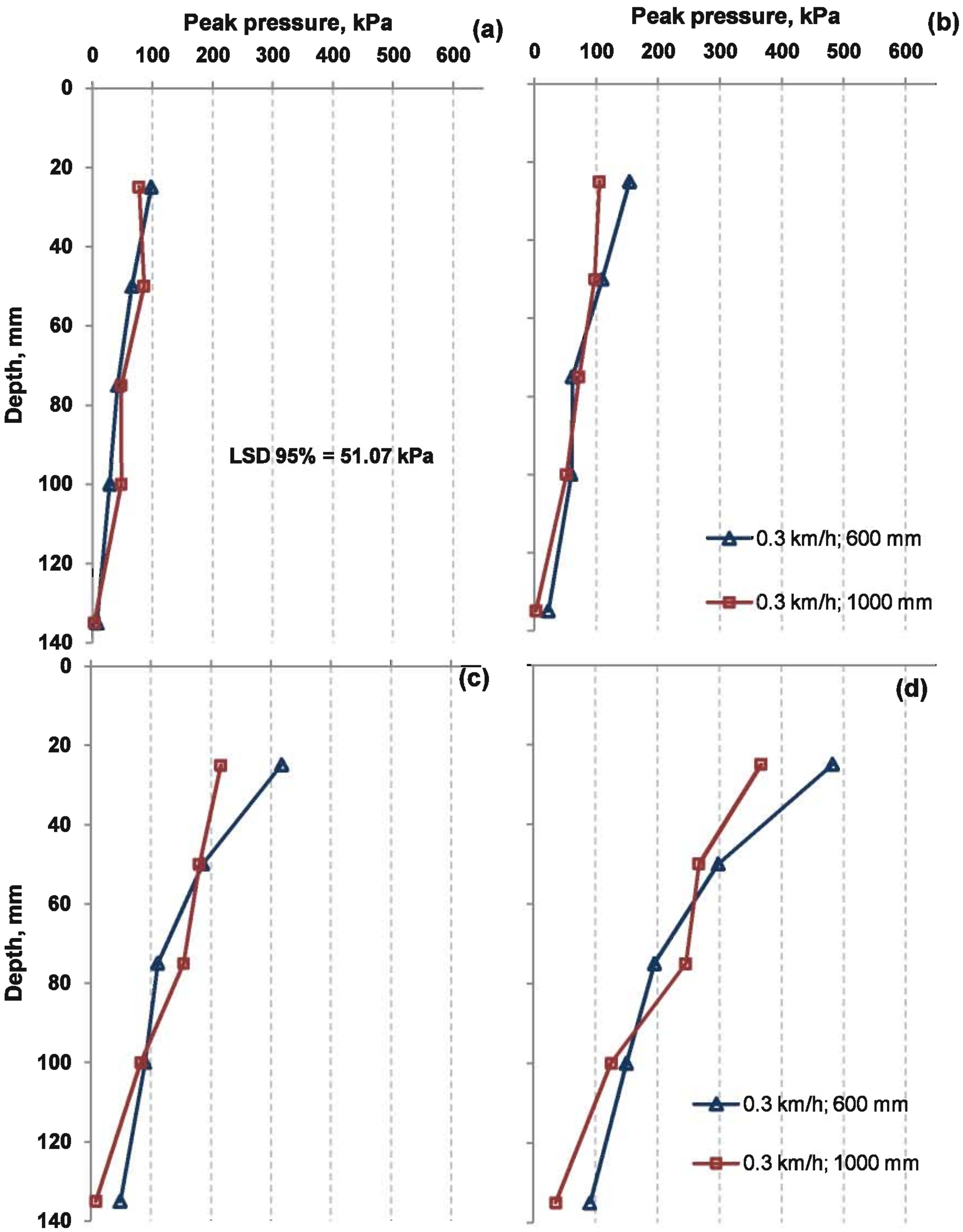

Figure 7.28 Peak pressure comparison between two roller diameters at five depths below rollers. (a) 260 kg m^{-1} roller, (b) 440 kg m^{-1}, (c) 840 kg m^{-1} roller and (d)1250 kg m^{-1}.

Pressure was significantly** greater at 75 mm depth for the 1000 mm diameter roller for the 1250 kg m^{-1} roller only, although this did not result in a greater increase in dry bulk density (see below).

7.3.4.3 Marker movement

Dry bulk density measurements from soil cores extracted from the soil profile after all roller passes indicated a tendency for higher density with the 600 mm roller in the top 80 mm depth although this was not statistically significant (Figure 7.29).

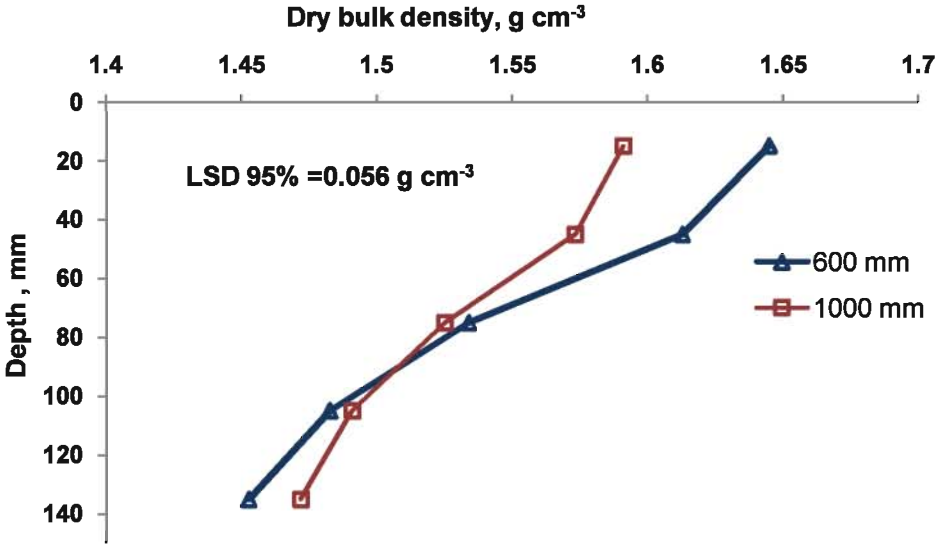

Figure 7.29 Final dry bulk density for soil profile after all roller passes of four roller weights.

Changes in dry bulk density with successive roller passes at all depths were significantly** different but not consistently so (Figure 7.30).

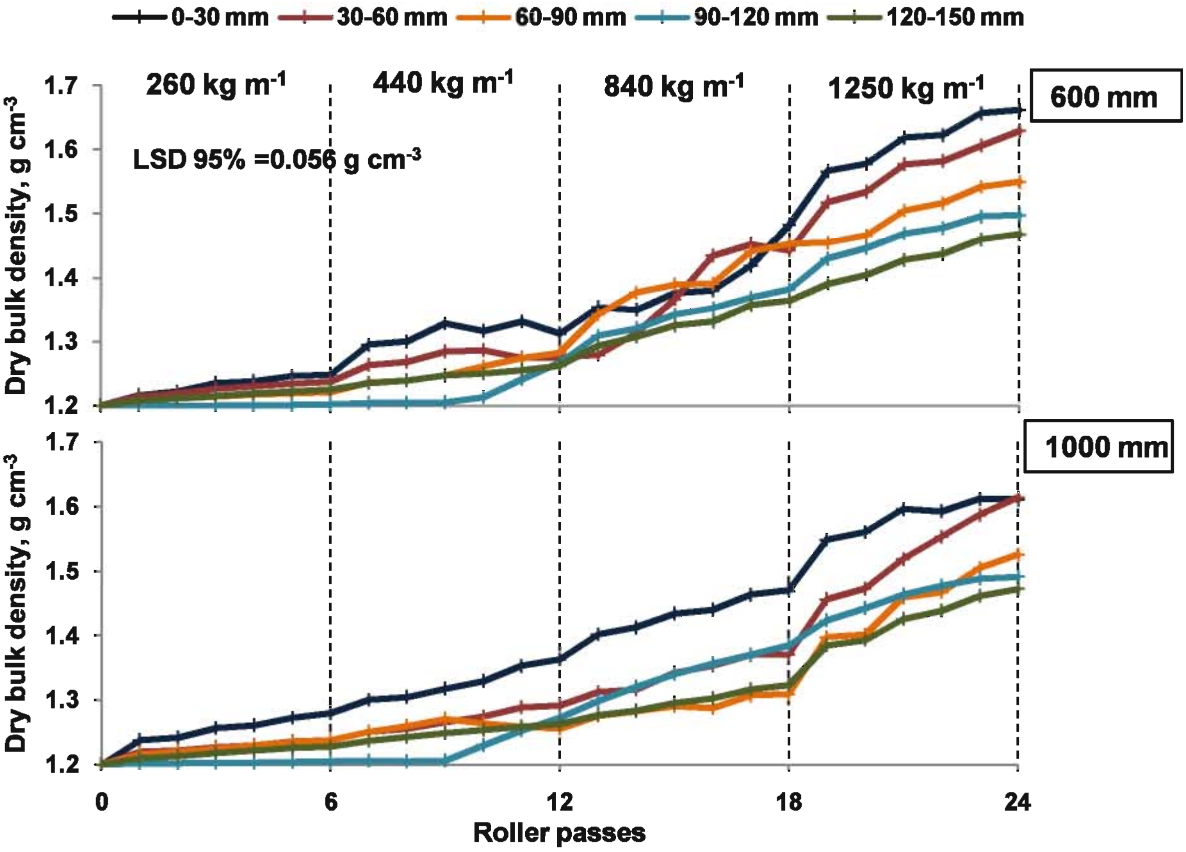

Figure 7.30 Profile dry bulk density change with roller passes for 600 mm and 1000 mm diameter rollers on a soil of 20% gravimetric moisture content.

Dry bulk density in the 0-30 mm depth was not significantly different for the two diameters for the two lightest rollers however there was a significantly** lower bulk density in the 30-60 mm and 60-90 mm depths for the 1000 mm diameter roller for all roller weights. The final density after 18 and 24 roller passes was significantly less for the 1000 mm diameter for the depths 0-30, 30-60 and 60-90 mm.

No significant differences were determined for maximum or permanent vertical displacement between the two roller diameters. Loading duration, maximum elastic displacement and permanent displacement were shown to be influenced by soil moisture in the previous section and the roller diameters were assessed on a soil of the same moisture content.

Significant** differences were determined for maximum and permanent horizontal displacement between the two diameters (Figure 7.31).

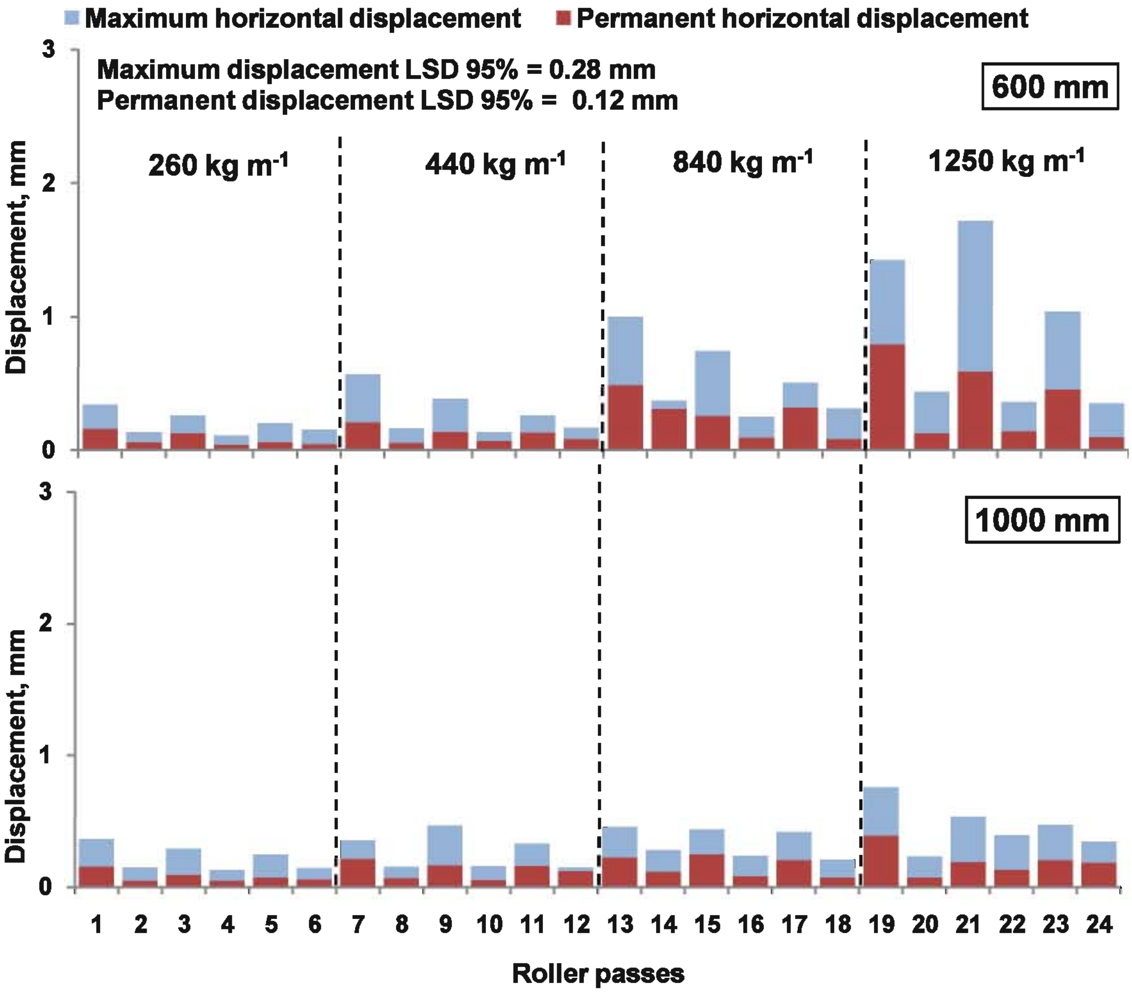

Figure 7.31 Maximum horizontal displacement and permanent horizontal displacement at 10-15 mm depth (marker depth reduces with increasing soil compaction i.e. roller passes) for all roller passes and two roller diameters. Significantly greater maximum and permanent displacement was determined for the 600 mm diameter roller compared to the 1000 mm roller for 840 kg m^{-1} and 1250 kg m^{-1} rollers.**

Mean maximum and permanent horizontal displacement were significantly** less for the 1000 mm roller compared to the 600 mm roller for the 840 kg m^{-1} and 1250 kg m^{-1} rollers (Table 7.4).

Table 7.4 Percentage reduction in mean horizontal movement resulting from a 1000 mm roller compared to a 600 mm roller.

	240 kg m^{-1}	440 kg m^{-1}	840 kg m^{-1}	1250 kg m^{-1}
Permanent displacement, %	7.03	-11.90	39.22	46.83
Maximum displacement, %	-8.88	5.18	36.63	49.06

Differences in horizontal movement were more apparent as roller mass increased and an illustration of the difference in marker movement is shown in Figure 7.32 for the 840 kg m^{-1} roller.

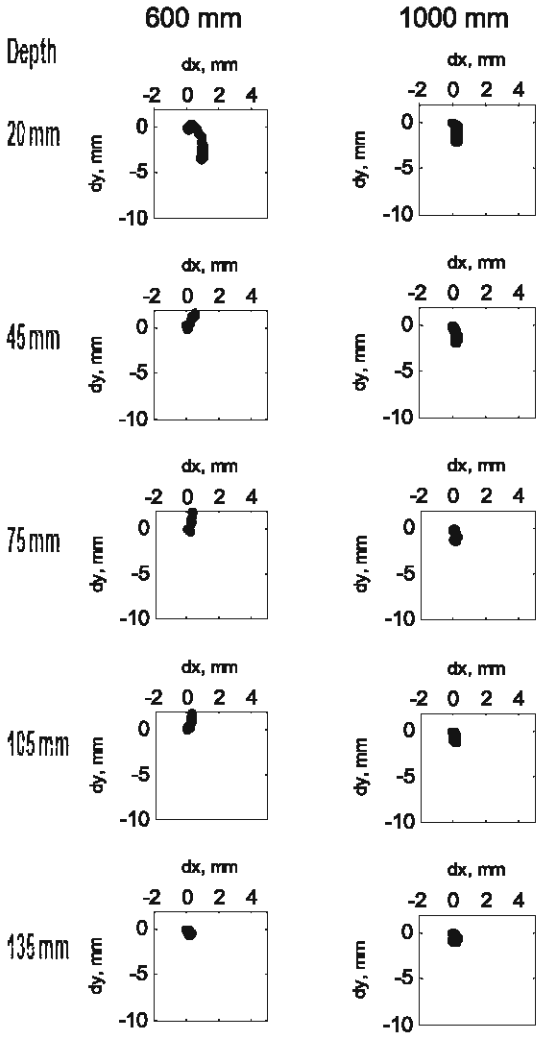

Figure 7.32 Marker movement for two roller diameters rolling a 20% moisture content soil at 1.35 g cm^{-3} dry bulk density with a 840 kg m^{-1} roller. Reduced horizontal movement occurred with the 1000 mm diameter roller. NB. Horizontal axis is magnified x2 c.f. the vertical axis.

A reduction in the soil roller contact angle resulting from a larger diameter will reduce the horizontal pressure in favour of an increase in vertical pressure (Figure 7.33).

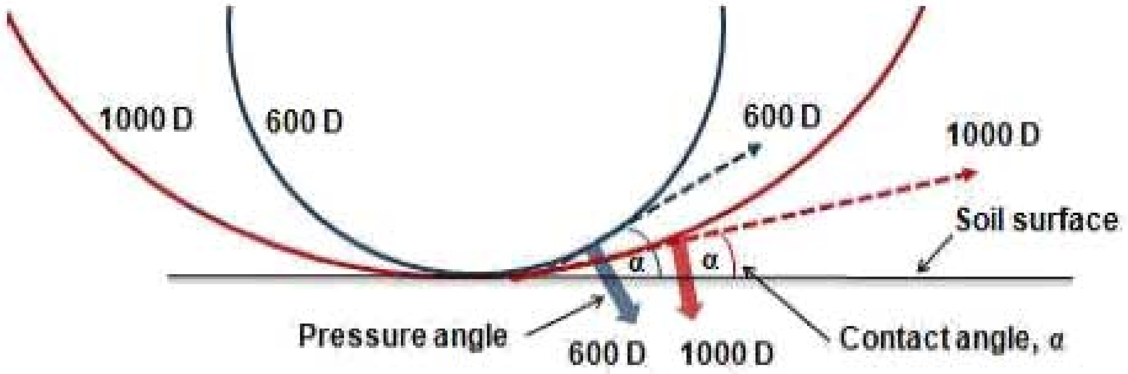

Figure 7.33 Diagrammatic representation of change in pressure angle resulting from a change in roller diameter. A larger diameter roller will have a reduction in horizontal pressure due to a decrease in soil/roller contact angle.

7.3.4.4 Summary of roller diameter experiments

Comparison between 600 mm and 1000 mm diameter rollers indicated that roller/soil contact increases with the 1000 mm resulting in a reduction in surface pressure and potentially a reduction in soil dry bulk density to a depth of 90 mm although this was only significant for the 1250 kg m^{-1} roller for 0-30 mm depth. Pressure was not significantly different below 30 mm. Horizontal elastic and permanent displacement were shown to be reduced with the 1000 mm roller for the 840 kg m^{-1} and the 1250 kg m^{-1} rollers. These results confirmed the hypothesis that different dry bulk density will occur through the soil profile as a result of different roller diameters however measurements of pressure were not consistent with this hypothesis.

7.3.5 Inclusion of grass roots in the soil profile

A soil bin was prepared with grass grown over the previous eight months (September 2007 to May 2008) to enable the adequate growth of grass roots throughout the soil profile (Figure7.34).

Figure 7.34 Soil bin with grass growth showing rooting throughout the 250 mm soil profile.

The soil was dried to approximately 25% gravimetric moisture content. The final soil profile was not evenly dry however and the moisture content increased with depth (25%, 26%, 26.5, 27% and 28% moisture content at 0-30 mm, 30-60 mm, 60-90 mm, 90-120 mm and 120-150 mm respectively). This profile was rolled in the same method as the previous experiments and the results compared to the 25% moisture experiment.

Results indicated no significant difference in overall profile dry bulk density change but starting densities were not uniform due to natural consolidation of the soil profile during the growing period.

7.3.5.1 Pressure distribution

Peak pressure with depth was significantly** different at depths 50 mm and 75 mm for three of the four roller weights (Figure 7.35).

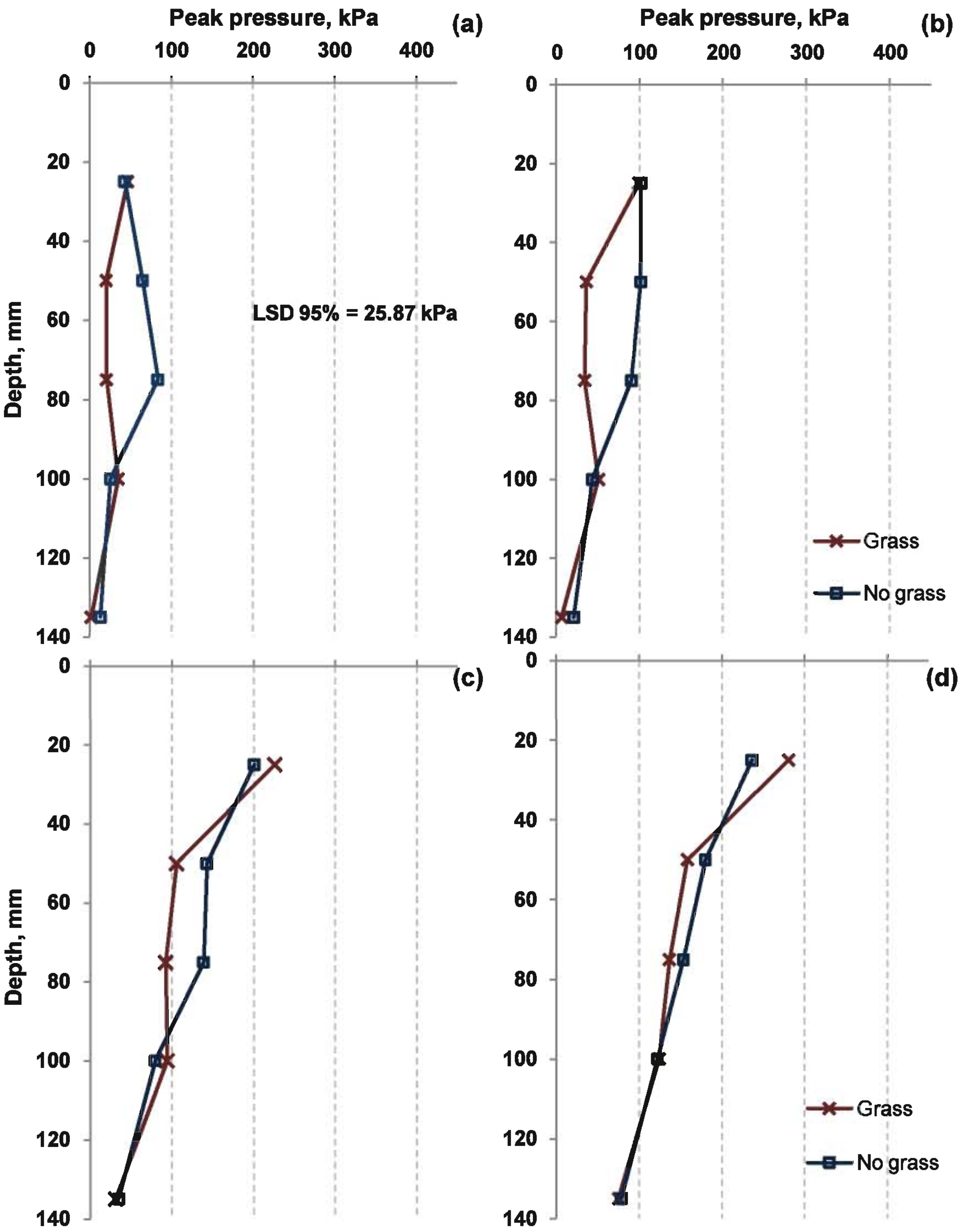

Figure 7.35 Peak pressure comparison between grass rooted soil profile and no grass soil, both at 25% moisture content, beneath a 260 kg m^{-1} roller (a), 440 kg m^{-1} roller (b), 840 kg m^{-1} roller (c) and 1250 kg m^{-1} roller (d).

Peak pressure declined between 25 mm and 50 mm at a faster rate for the grass treatment. Roots increase elastic energy dissipation resulting in a faster decline in pressure with depth. A reduction in porosity of soil has been shown to occur when roots grow into a compacted soil (Dexter, 1987) reducing available void space to increase bulk density. This increases soil strength and stiffness and also reduces pressure more quickly due to the increase in work done.

Roller pressure duration increased with grass treatments also indicating a stiffer soil (Figure 7.36).

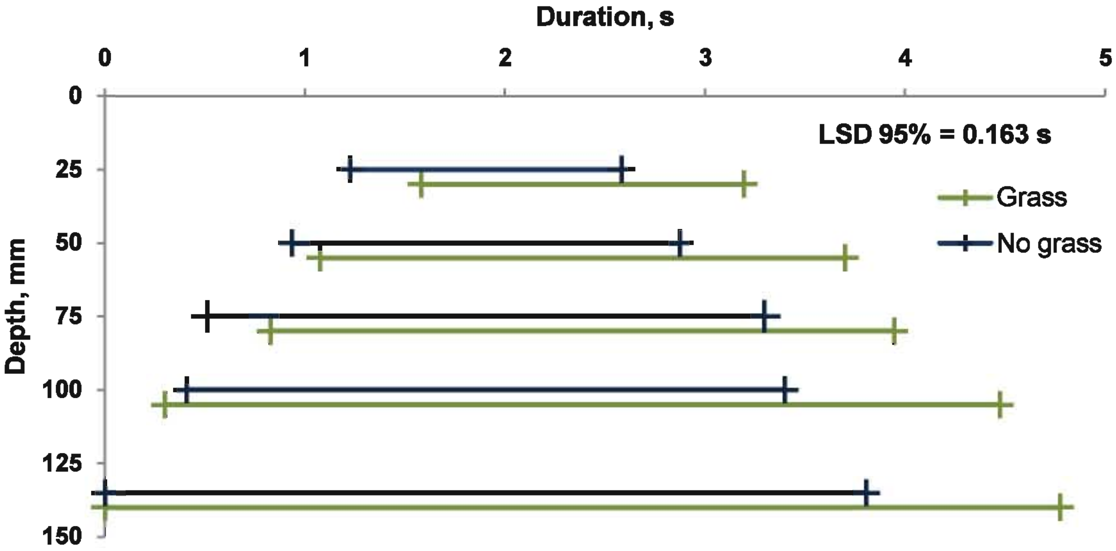

Figure 7.36 Duration of pressure for a 600 mm diameter roller for grass and no grass treatments. Significantly longer duration at all depths for the grass treatment was determined.**

7.3.5.2 Marker movement

Marker movement analysis for vertical displacement determined significantly** greater maximum vertical displacement for the grass for three of the four roller weights but an inconsistent difference in permanent displacement (Figure7.37). An increased maximum displacement from the grass treatments compared to permanent displacement indicated greater elasticity from the grass profile.

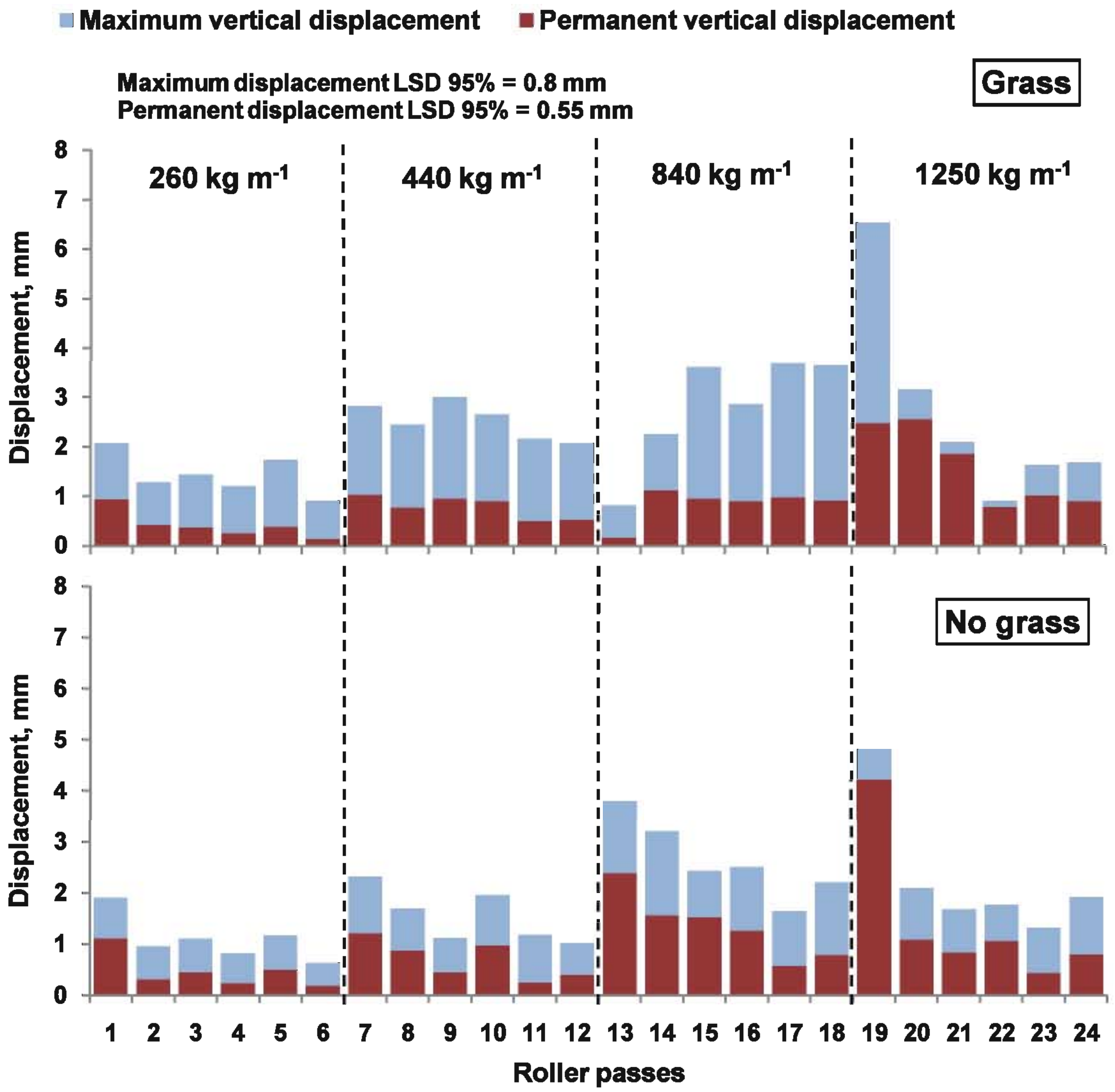

Figure 7.37 Maximum vertical displacement and permanent vertical displacement for grass and no grass treatments at 15 mm depth. Significantly greater maximum displacement compared to permanent displacement was determined for grass treatments.**

Final profile dry bulk density indicated a significantly** lower density at all depths for the grass treatment which is at least in part due to the lower density (specific weight) of root compared to soil (Figure 7.38).

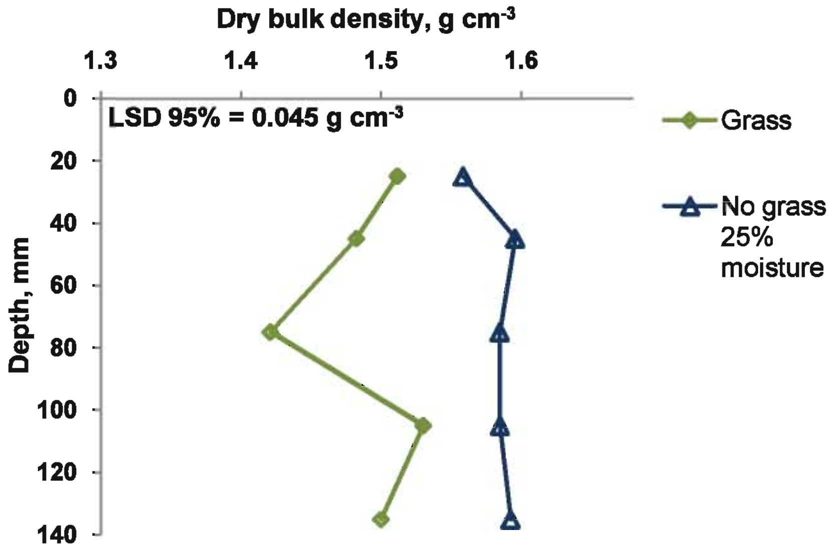

Figure 7.38 Final dry bulk densities at depth to 150 mm for grass and no grass treatments. Significantly greater dry bulk density at all depths for the no grass treatment was determined.**

At the 0-30 mm depth the grass roots will reduce dry bulk density by forcing soil particles apart. At depths 50 mm and 75 mm the reduced dry bulk density can be associated with the reduced pressure reaching these depths. For depths below 90 mm the soil reached a dry bulk density and moisture combination that resulted in zero air voids.

A combination of the reduced pressure at depth and higher moisture content combined with the lower specific weight of grass roots resulted in a lower dry bulk density for all roller depths at the 30-60 mm and 60-90 mm depths for the grass treatment (Figure 7.39).

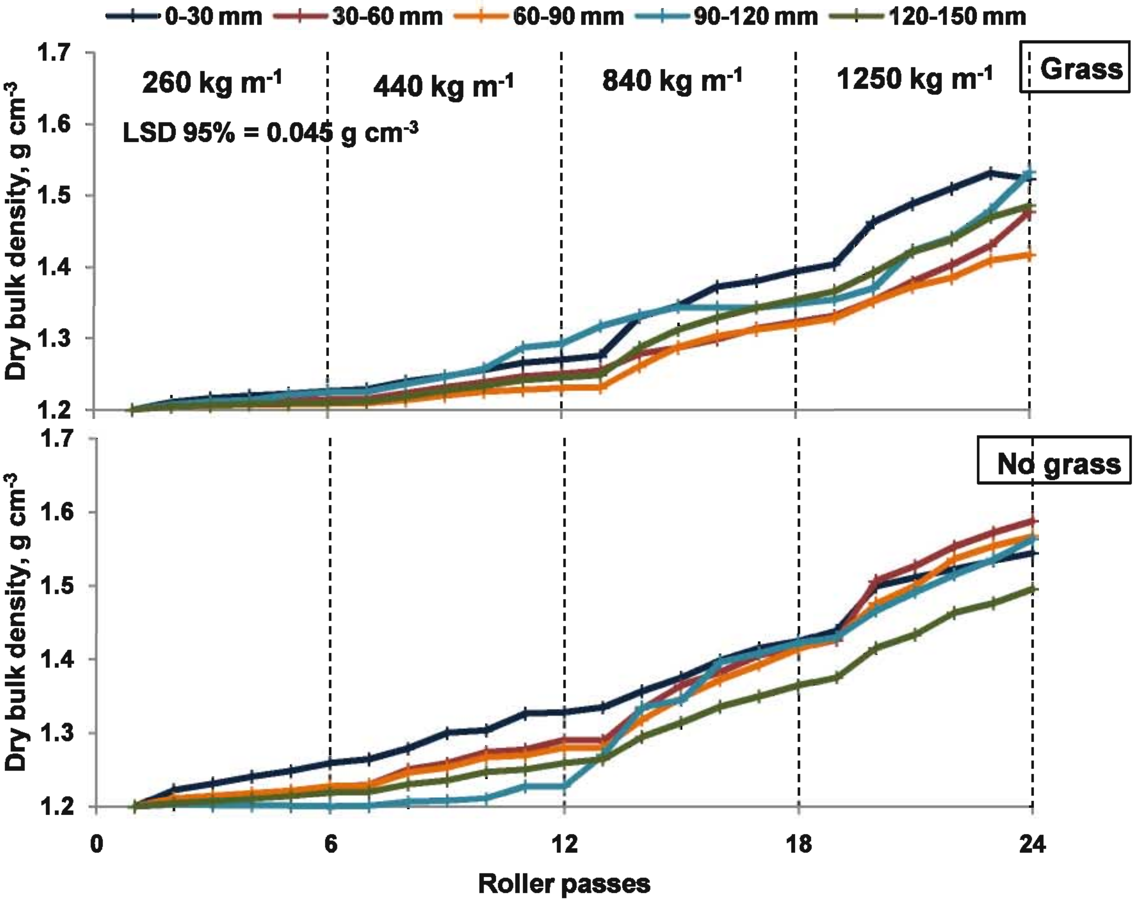

Figure 7.39 Dry bulk density change with successive roller passes for soil grass and no grass treatments at 25% moisture content.

Analysis of horizontal soil movement determined significantly** less maximum horizontal displacement in the grass treatment compared to the soil with no grass roots for three of the four roller weights (Figure 7.40).

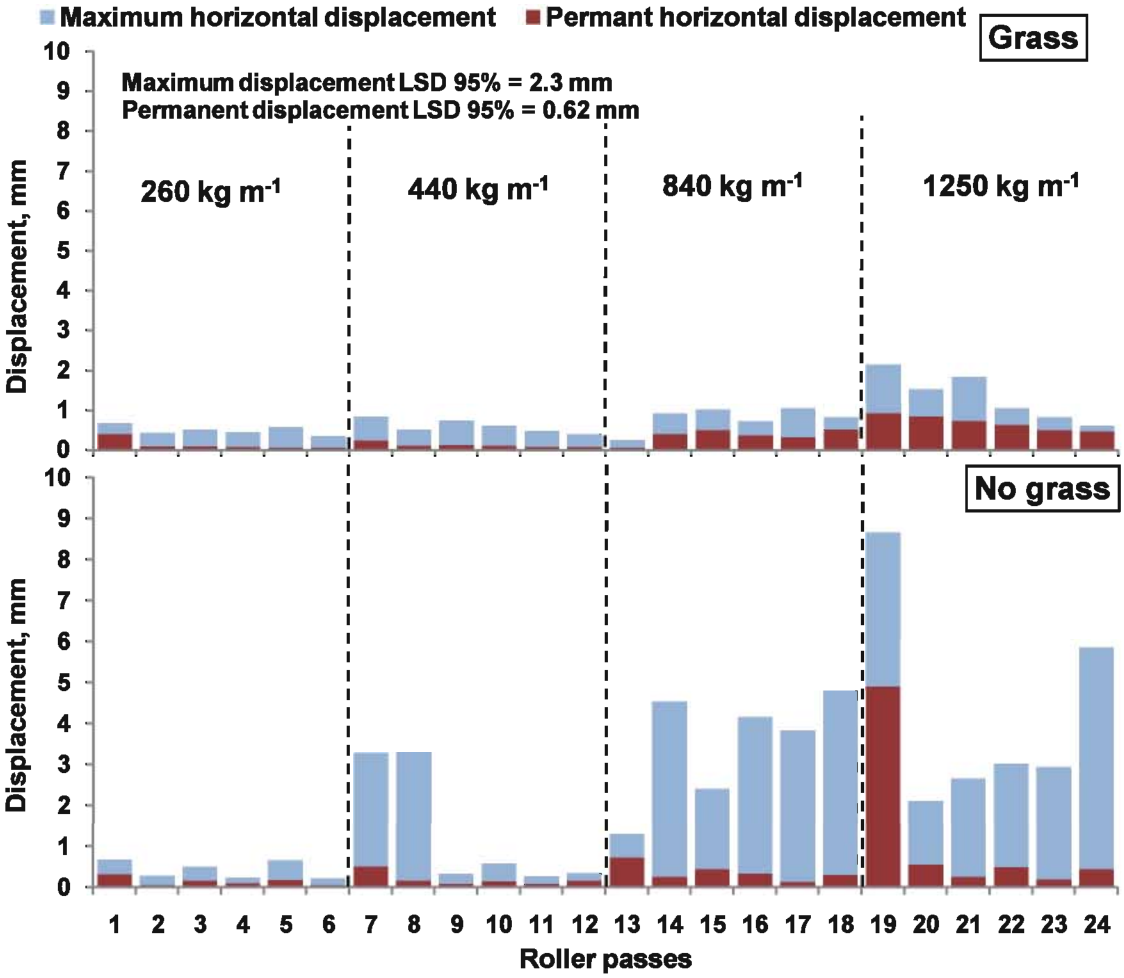

Figure 7.40 Maximum horizontal displacement and permanent horizontal displacement for all roller passes for grass and no grass treatments. Significantly less maximum horizontal movement occurred with the grass treatment.**

Grass roots increase soil strength (Tengbeh, 1993; Van Wijk, 1983) and provide resistance to an applied force. Rootmass that is perpendicular to the horizontal component of force of the roller will resist strain and reduce rootzone movement. The amount of force applied will increase with roller weight which will at some point surpass the strength of the root causing it to yield by either moving position or breaking. Continuous stress applied by a roller with repetitive roller passes in opposite directions could potentially cause permanent root damage although the point at which this happens was not determined.

7.3.5.3 Summary of rolling simulator grass experiment

The inclusion of grass into the rootzone was shown to increase soil stiffness and elasticity. A faster decline in pressure with depth occurred and a subsequent reduction in dry bulk density in a soil with 25% moisture content. It was also determined that the strength contributed to the soil rootzone by grass roots significantly** reduce horizontal movement however the stress on roots in these conditions could result in root damage.

7.4 Discussion of cricket rolling simulator

7.4.1 Soil moisture – Hypothesis 1

The results from the moisture experiment confirm the principles set out in Hypothesis 1. A reduction in soil stiffness with an increase in soil moisture increases the potential to increase dry bulk density with a given load and increases horizontal and vertical displacement. Moisture contents above the Proctor optimum resulted in an increase in dry bulk density to a greater depth but final density was restricted by low levels of air voids as the soil density increased. Lower soil moisture content increased the soils strength and stiffness, with lower plastic strain reducing soil compaction.

Differences in horizontal movement between soils of different soil moisture content could cause horizontal shearing between soils that have an abrupt change in soil moisture content with depth. This scenario could occur in cricket soils with inadequate irrigation management or lack of awareness of soil moisture following natural precipitation resulting in the soil moisture content in the top of the profile, up to approximately 50 mm, overlying soil of lower moisture content. This could be crucial in the establishment of horizontal layering and root breaks commonly occurring in cricket soils.

Some parallel cracking of the surface was observed following rolling with the heaviest two rollers in the 25% moisture soil. These reduced with successive passes as soil compaction increased. This is likely to be due to the increased horizontal soil movement in soils with higher moisture content. This was also observed by Jarzebowski *et al* (1998) (Section 1.5.3.1) and could be a factor in the initiation of surface cracking in cricket pitches.

7.4.2 Roller weight and roller passes – Hypothesis 2 and 3

Maximum densities achieved by different roller weights indicate that optimum moistures for cricket pitch rolling will depend on the roller mass.

For each increase in roller mass a significant increase in dry bulk density occurred for the first roller pass with additional increases in dry bulk density reducing with successive roller passes. A roller configuration that has a compactive potential greater than the soil dry bulk density that it is rolling will increase density with a rolling pass. Soil strength increases with an increase in soil bulk density requiring a greater force to move soil particles. Subsequent passes will have a reduced permanent soil bulk density change and an increase in elastic recovery. The initial roller pass expends energy in compacting soil closest to the roller/soil contact reducing pressure at lower depths. Subsequent roller passes can result in greater pressure at lower depths with a consequential increase in soil bulk density.

Reduction in permanent vertical displacement within the soil profile is also accompanied by reduced elastic displacement as soil strength increases. Successive roller passes increasing dry bulk density will increase soil strength to a point where the force required to move soil particles closer together is greater than the roller capability and no further increase in dry bulk density will occur. At this point elastic strain, both horizontal and vertical, reaches a constant level if all roller and soil physical parameters remain constant. This reduction in bulk density with consecutive passes is, in part, prolonged by the reduction in roller contact resulting from the increase in soil stiffness which in turn increases soil surface pressure.

Increase in dry bulk density was determined to require no more than seven roller passes to achieve 100% of the total density increase. Cricket rollers with two roller drums should therefore achieve 98% of potential dry bulk density increase with the first three roller passes (i.e. 6 roller drum passes). No difference was determined between moisture, or grass and no grass treatments, for the amount of roller passes required to increase dry bulk density. This does not concur with Parsons (1992) who determined a reduction in roller passes for up to a 4% increase in soil moisture over the Proctor optimum.

7.4.3 Roller speed – Hypothesis 4

Roller speeds of 0.3 km h^{-1} and 0.6 km h^{-1} resulted in similar densities at all depths and all roller weights. Duration of pressure from a moving roller reduced in line with speed reduction but this had no effect on changes in dry bulk density. A tendency to reduce horizontal movement at the faster speed was observed although this was not statistically significant and could be investigated further in future work.

7.4.4 Roller diameter – Hypothesis 5

The increase in roller/soil contact resulting from a larger roller diameter reduced contact pressure and showed a tendency to reduce increases in dry bulk density at depths to 90 mm. Differences in dry bulk density between these two diameters were small in terms of cricket pitch densities and would probably not enable a justification to recommend one diameter over another. Horizontal elastic and permanent displacement was reduced with the 1000 mm roller due to a smaller soil/roller contact angle. As suggested above, horizontal strain could cause root or soil profile damage and therefore a larger diameter roller could reduce this problem. However the greatest horizontal displacement occurred in 25% moisture content soil which was not tested with the 1000 mm diameter roller. The 1000 mm diameter roller indicated a reduction of up to 49% in maximum horizontal movement for a roller mass of 1250 kg m^{-1}.

Further work needs to be done to investigate the influence of roller diameter on soil compaction. Although larger diameters may reduce horizontal soil movement, a reduction in bulk density with depth will occur. Increasing the roller weight to compensate may increase roller sinkage and increase soil contact angle and therefore horizontal strain.

7.4.5 Grass roots in the soil profile – Hypothesis 6

The working hypothesis that grass roots will increase the force required to compact soil was confirmed resulting from the increase in stiffness of the soil profile, attributed to the grass roots, and the increased elasticity from the rootmass material. The contribution of roots to soil strength also reduces horizontal displacement and, whilst grass strength limits are not exceeded, reduces the potential to cause horizontal shearing in the soil profile. High levels of stress or repeated stress from successive roller passes could damage grass roots and reduce the plants efficiency. Grass root orientation is generally vertical and therefore reinforces the rootzone against horizontal stress. The effect on vertical deformation is lower due to the compressibility of roots.

Chapter 8. Discussion

8.1 Introduction

Results of the survey of cricket rolling management provided justification for this rolling project by determining a wide variation in rolling practice at all levels of the game. This was particularly the case for the timing of rolling and time spent rolling, as well as equipment availability and specifications, both among all facilities and between facility types.

Characterisation of the cricket soils used in the experiments was conducted on the basis of a working hypothesis that 'soil mechanical properties change in relation to the soil moisture content thereby affecting the load required for compaction'. Soil strength parameters indicated a reduction in soil strength with an increase in moisture content and/or a reduction in dry bulk density, with a consequential reduction in pressure required to increase soil bulk density. A reduction in plastic strain with consecutive equal loads was identified.

To account for the effects of natural climatic change on soil and the strength characteristics of grass, field experimental plots were constructed. Assessment of rolling effectiveness under a range of soil physical conditions and roller configurations confirm soil water as a limiting factor in roller compaction. Assessment of soil moisture during summer pitch preparation was complimented by a grass root experiment which also aimed to determine root penetration and distribution in compacted cricket loams.

The effect of rolling on changes in bulk density can be assessed retrospectively after rolling. However soil movement under a smooth-wheeled roller during rolling needed to be studied to determine differences in vertical and horizontal elastic-plastic soil movement in different soil moisture conditions. A cricket rolling simulator was designed and built for this purpose.

The experimental parameters evolved over time as a result of a learning process from experiments which lead to some inconsistencies between experiments for soil moisture content and initial dry bulk density. With much of the experimental focus being on determining the maximum dry bulk density achievable with a given force at a specific moisture content, the variation in soil moisture content was necessary in order that optimum moisture contents for specific roller weights could be determined. The cricket rolling simulator moisture contents were selected to encompass the range of soil moisture contents encountered in other experiments, either naturally occurring or manipulated, and also because four roller weights with different optimum moisture contents were tested simultaneously on the same soil profile. This did enable the determination of different soil movement resulting from rolling in relation to soil moisture however.

8.2 Conceptual model of cricket pitch rolling

Essentially cricket pitch soil compaction can be conceptualised as a 3-way interaction between soil moisture content, soil dry bulk density and roller force. Fundamentally soil moisture and dry bulk density are intrinsic components of the soil's mechanical properties and the effectiveness of a roller in increasing soil dry bulk density will depend on the roller's compactive force in relation to these mechanical properties (Figure 8.1).

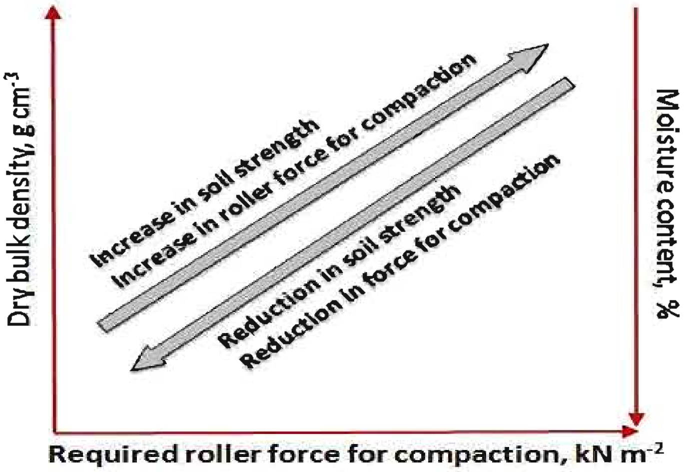

Figure 8.1 Idealised 3-way interaction between soil moisture content, soil dry bulk density and roller load.

Conceptually the research considers the relationship in more detail and considers the interaction between soil mechanical and roller physical properties. The soil mechanical properties are fundamentally a result of soil physical properties i.e. moisture content, mineral composition, organic matter and soil bulk density (and hence porosity).

8.2.1 Soil mechanical properties

Soil moisture content is crucial to the concept of compaction due to the effect of water on inter-particle friction and soil cohesion which affect the soils strength. The strength of soil determines the force required to increase the dry bulk density which in turn influences the roller compactive pressure required to achieve a desired increase in density. Triaxial and translational shear strength test results indicated a decline in soil strength from 120.5 kN m^{-2} to 41.9 kN m^{-2} as soil moisture content increased from 15% to 23%.

The elastic-plastic behaviour of soils during compression will be dependent on soil strength and is therefore also affected by soil moisture content and bulk density. An increase in soil moisture content normally reduces soil strength resulting in an increase in plastic strain and elastic movement. However as water is not compressible it can also increase soil stiffness should water movement within the soil voids not be possible, due to limited air voids or speed of loading. Vertical compression in saturated soils will exhibit a high level of stiffness whereas horizontal shear could occur due to the low shear strength.

Soil characterisation using dynamic triaxial testing results confirmed the relationship between elastic-plastic behaviour of cricket soils and soil moisture content and identified potential pressure minimums required to compact soil of different dry bulk density and moisture content. Rolling simulator marker movement analysis confirmed the influence of soil moisture on soil stiffness where it was determined that soils with a moisture content of 25% had a greater plastic strain for a given load for both vertical and horizontal soil movement compared to the 20% and 16% moisture content. The plastic limit for the OL and KL soils was 20.6% and 21.1% respectively indicating a greater degree of soil plasticity above these moistures. Horizontal elastic movement was also greater for the 25% moisture content soil although vertical elastic movement was not different.

Optimum moisture content is the moisture content that enables the maximum dry bulk density to be achieved with a particular compactive force. This will be different for each roller configuration with a lower roller weight having higher optimum moisture content due to the lower achievable maximum dry bulk density. A reduction in soil strength with an increase in moisture content (to an optimal limit) enables an increase in the achievable dry bulk density with a roller providing the soil has adequate air voids. Minimum air voids of 3% - 5% are necessary to avoid increasing vertical stiffness and were shown by field experiments and others (Parsons, 1992). Compaction experiments indicated a 1.68 g cm^{-3} standard Proctor optimum dry bulk density with an optimum moisture content of 19.1%. Field and simulator experiments indicated a range of lower maximum densities for different roller weights which when assessed for moisture content at 5% air voids confirms the need for higher optimum moisture content. This optimum moisture content ranged between 24% and 22% for rollers achieving 1.55 g cm^{-3} and 1.61 g cm^{-3} for KL and OL soils respectively.

Saturation moisture content was shown to increase with a reduction in soil dry bulk density due to the increase in porosity. Although initial drying rates were greater for the lower bulk density soil, target moisture content for cricket playability may not be achieved in the required timeframe.

Changes in dry bulk density have been shown to alter the load required for compaction however soil bulk density is not static in cricket pitches, even without the intervention of rolling. This is due to the natural consolidation over time and variation in clay soils through shrink/swell characteristics resulting from changes in moisture content. Other pitch management operations will also contribute to changes in pitch dry bulk density i.e. decompaction. Results show significant reductions in dry bulk density from increases in moisture content both during irrigation and seasonal rainfall as well as over a longer winter period. Subsequent drying of soil increased dry bulk density of the soil but not to the same level as that prior to wetting.

Differences in organic matter content have been shown by others (Baker *et al,* 2003a; Baker *et al,* 2003b) to alter soil physical properties and influence cricket playability parameters. This study did not evaluate the effect of organic matter on soil compaction.

8.2.2 Grass and soil/rootzone mechanical properties

Soil mechanical properties are influenced by the strength of grass roots growing in the soil profile. The increase in strength of the soil rootzone increases the compactive force required to increase soil dry bulk density.

Shear strength was shown to increase with an increase in grass roots in the field experiments. Rolling simulator experiments determined a reduced vertical permanent plastic soil movement for treatments with grass which was due to an increase in soil strength resulting from the reinforcing effects of grass. A significant reduction in horizontal soil movement was also determined in simulator experiments as a result of the inclusion of roots into the soil profile.

Grass roots in the profile were shown to change soil structure resulting in an increase in soil drainage and drying properties. Roots also play an important function in the soil moisture component of soil mechanical properties through transpiration.

Rooting into compacted soil is influenced by soil particle size distribution and soil dry bulk density which can potentially influence the soil mechanical properties. Grass rooting experiments determined a lower total rootmass for the OL soil which had a lower median particle size (D_{50}) of 11 μm compared to the KL D_{50} of 45 μm.

8.2.3 Interaction of the smooth-wheeled roller

It has been established that the pressure required to increase soil dry bulk density increases with soil strength. Therefore an increase in roller applied stress is required as soil strength increases. The stress applied by the roller is related to roller mass and soil/roller contact area which in turn is influenced by soil strength. Rolling simulator results showed that soil/roller contact is influenced by:

- Increase in roller mass increases soil/roller contact due to the increase in pressure on the soil surface which can actually reduce applied stress.
- Increase in soil moisture increases soil/roller contact due to a reduction in soil strength and this reduces applied stress.
- An increase in roller diameter will increase the contact arc length and reduce the angle of soil/roller contact and therefore reduce contact stress.

Although contact pressure reduces with an increase in soil moisture, the pressure required to achieve permanent strain changes is also reduced as evidenced above.

Roller mass directly relates to pressure beneath the roller in the soil profile for given soil physical parameters and roller diameter/width. Work done or energy dissipation in compacting soils is higher in wet and loose soil conditions. Simulator experiments showed that consecutive roller passes increase soil dry bulk density and the resulting increase in stiffness increased pressure to lower depths giving an increased potential to increase dry bulk density at these depths.

Results from all experiments verified the hypotheses that:

- An increase in roller mass increases the potential to increase dry bulk density.
- Optimum moisture above the standard Proctor optimum is needed for rollers that have a compactive potential below Proctor maximum dry bulk density.

The results are summarised in Figure 8.2.

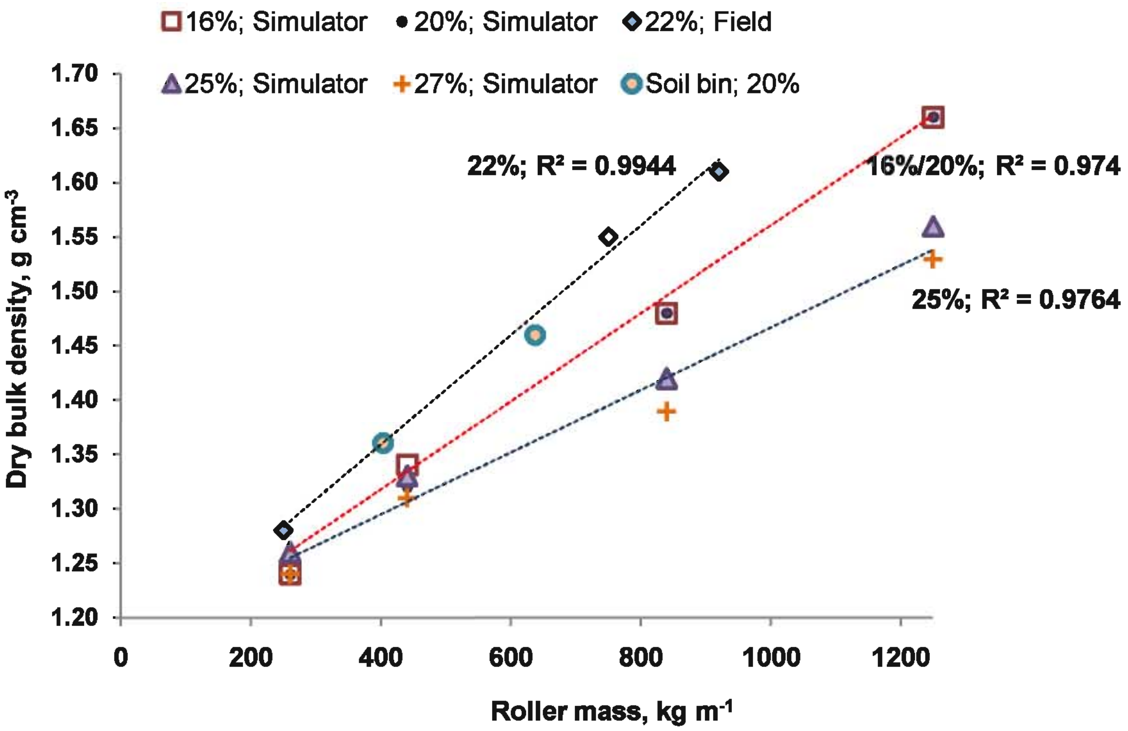

Figure 8.2 Maximum dry bulk densities achieved with all roller weights and a range of experimental moisture contents in the 0-50 mm depth. Linear trendlines indicate consistent relationships with soil moisture content (within the range studied). The optimum moisture was only determined for the field experiment roller configurations.

Roller speed was not shown to influence compaction of cricket soils for the range of speeds examined in the rolling simulator (0.3 and 0.6 km h^{-1}), soil bin (1.0 and 2.0 km h^{-1}) and the field experiments (0.45 and 0.9 km h^{-1}). Extremes were not compared i.e. 0.3 km h^{-1} and 2.0 km h^{-1} however in the speed range currently undertaken by groundsmen (as evidenced in the rolling survey), no change in practice would be necessary. Low roller speed did not indicate a significant increase in vertical plastic or elastic movement compared to a faster speed for speeds associated with cricket pitch rolling.

An increase in roller diameter will reduce the soil/roller contact angle and therefore reduce the amount of horizontal stress applied to the soil in favour of greater vertical stress. A 1000 mm diameter roller was shown to reduce maximum horizontal strain by up to 49%, for a roller mass of 1250 kg m^{-1}, compared to a 600 mm roller in soils with a moisture content of 20% and a dry bulk density of 1.50 g cm^{-3}.

8.2.4 Roller passes

An initial roller pass, with a roller that has a compactive potential above the current dry bulk density in the given soil moisture conditions, will increase soil density. This increase in soil dry bulk density will require the lowest pressure of a series of consecutive roller passes and therefore the pressure required to induce permanent plastic strain will occur for a longer duration as the roller passes. The differential between pressure required for compaction and available pressure will also be at its greatest. The following roller pass will have a reduced pressure differential due to an increase in soil dry bulk density which increases soil strength and therefore requires a greater pressure to induce plastic strain. This higher pressure requirement will reduce the duration that the soil has this pressure applied by the passing roller and the corresponding increase in dry bulk density is also reduced. For each consecutive roller pass the soil strength increases and the compactive potential of the roller becomes closer and the pressure required to increase the dry bulk density becomes closer to the peak pressure potential from the roller. This process is slowed to a certain extent due to the soil/roller contact area reducing with successive passes due to the increase in soil strength reducing roller sinkage. This increases the contact pressure and increases the roller compactive potential.

The differential between the initial soil dry bulk density and the roller compactive potential will influence the amount of change in dry bulk density and the required roller passes to achieve it.

Experimental results from field experiments determined an average increase of 0.015 g cm^{-3} for a pass of the 750 kg m^{-1} and 920 kg m^{-1} two drum rollers; per roller drum this equates to 0.0075 g cm^{-3}. Rolling simulator results indicated a mean increase per roller pass of 0.0073 g cm^{-3} but this varied according to roller mass and dry bulk density gain, (0.0018, 0.0044, 0.0095 and 0.0089 g cm^{-3} for the roller masses 220, 440, 840 and 1250 kg m^{-1} respectively). The soil bin experiment indicated larger increases, 0.015 and 0.035 g cm^{-3} (403 kg m^{-1} and 638 kg m^{-1} roller mass respectively) for each roller pass due to the larger differential between initial dry bulk density and roller compactive potential (final dry bulk density). These results were in agreement with other work (DSIR 1951) for rollers in a similar specification range.

The number of passes required to compact a cricket pitch will depend on the initial dry bulk density and the compactive potential of the roller. Rolling simulator data indicated that all compaction is achieved after a maximum of seven roller (single drum) passes regardless of moisture and dry bulk density achieved, with 98% of final compaction being achieved after six roller (single drum) passes. Field experiments where small increases in dry bulk density were achieved required a maximum of four roller passes (two roller drums; equivalent to eight single drum roller passes). Soil bin rolling required 10 single drum passes due to the larger overall increase in dry bulk density.

The conceptual model highlights the importance of soil moisture content in the efficient compaction of cricket soils in a dry bulk density range between 1.20 and 1.80 g cm^{-3}. Optimum moisture content is dependent on roller compactive potential and is at approximately 5% air voids at the point when maximum dry bulk density is achieved. Maximum dry bulk density potential is largely dependent on roller mass in conjunction with the optimum moisture content, although soil contact area influences contact pressure and is again affected by soil moisture and bulk density. Final dry bulk densities for pitch preparation will be greater than the roller's compactive potential, should the pitch be allowed to dry below the optimum rolling moisture content, due to soil shrinkage.

8.3 Practical considerations for cricket pitch rolling

Experimental data provided evidence of a number of practical aspects of cricket pitch preparation which could be of use to cricket groundsmen and should be considered as part of the final guidelines for cricket pitch rolling.

8.3.1 Soil moisture characteristics

Changes in soil moisture content alter soil bulk density as a result of the expansive clay minerals in the soil. Prolonged saturation during winter months was shown to reduce soil dry bulk density but the results were inconsistent between the years studied and are likely to be weather dependent. Soil expansion after rainfall and irrigation in the summer pitch preparation period also occurred in the field experimental plots. Drying of the soil causes soil shrinkage resulting in an increase in soil dry bulk density. The shrink/swell nature of soil, particularly in the top 50 mm of the soil profile requires understanding from groundsmen. Once rolled, a pitch will not necessarily stay compacted should the soil moisture content increase and may require rolling again although some of the expansion will be countered by shrinkage as the soil dries.

The current practice of regular rolling as the pitch dries reduces the need for knowledge of the actual pitch moisture content on the basis that at some point rolling will occur in optimum soil moisture conditions. Without accurate soil moisture measurement it may not be prudent to recommend a strategy of limiting rolling to specific moisture content ranges, although it could be more efficient to do so.

With soil moisture content for optimum rolling being established as dependent on roller compactive potential, the likely moisture content range for most cricket roller configurations is 22% to 24% (for rollers achieving 1.61 and 1.55 g cm^{-3} respectively). The timing of rolling is crucial to achieving the most efficient soil compaction.

Early spring rolling reduced moisture content later in the spring in the field experiments due to the increase in dry bulk density, particularly in the 0-60 mm depth compared to an unrolled control. Compaction of this depth will reduce hydraulic conductivity through the soil profile from further rainfall although a period of prolonged precipitation could gradually allow infiltration into the clay loam soil resulting in re-expansion. This process will be weather dependent and therefore unpredictable. It is also influenced to a certain extent by soil type, with the OL soil having a greater fluctuation in soil densities from moisture content change due to the higher content of expansive clay minerals. Rolling, followed by covering to protect the pitch from further excessive rainfall will enable lower soil moisture content later in the spring. If pitch covers are not available then re-rolling after a period of rain may be appropriate but will effectively restart the compaction process to a previous dry bulk density level rather than add to the density.

Not rolling low bulk density pitches pre-season in the spring could result in higher moisture contents at the start of the playing season due to higher pore volume allowing a greater potential to store water. This may also be the case in pitches which are inherently high bulk density but that have experienced soil expansion in the 0-60 mm depth following winter. The benefit of early pre-season rolling is essentially moisture control as rolling later in the spring can still achieve the same final densities. However leaving rolling until later could result in delays waiting for the soil to dry, or match day moisture may be higher than desired for early season fixtures.

It is not possible to have a stated start date for spring rolling due to the UK's variable climate but rolling is unlikely to be effective in high clay cricket loams without a prolonged dry period (both from humidity and rainfall). Covering pitches will prevent re-saturation however humid air conditions restrict evaporation and therefore drying will still be slow but may be necessary for facilities with early fixtures. Lower clay content soils will dry more quickly but will still require a prolonged period of dry weather in early spring before rolling is effective.

When grass growth begins, which is also weather dependent, the speed of drying will increase due to an increase in evapotranspiration, and this is likely to be the time when rolling will become more effective.

Drying in the summer will be more rapid than in the spring as a result of faster grass growth and generally warmer and less humid air increasing evapotranspiration. However this will vary considerably throughout the summer and between venues. Comparison of drying rates between the grass rooting experiment 1.60 g cm^{-3} dry bulk density treatment and the comparable pitch drying field experiment for the 0-60 mm depth indicated a range in days when moisture contents will reach optimum conditions for the two soils (Figure 8.3).

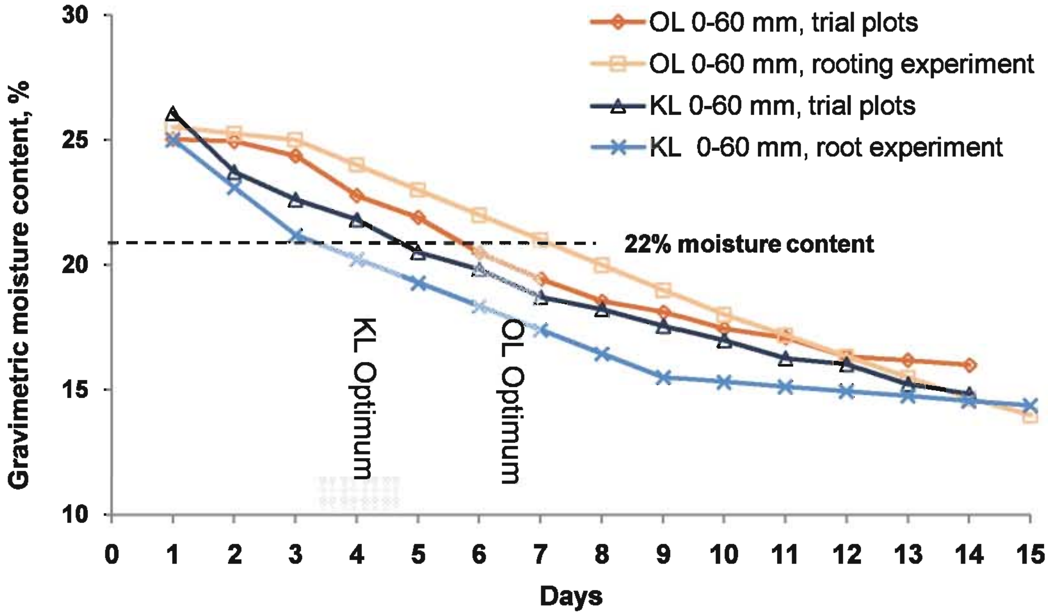

Figure 8.3 Gravimetric moisture content after initial saturation for KL and OL soil in the 0-60 mm depth with an approximate dry bulk density of 1.60 g cm^{-3}. July and August 2007. KL soil reached 22% moisture in 3-5 days whereas OL soil took 6-7 days. Optimum moisture content ranges for rolling are highlighted for each soil.

The grass root and trial plot experiments were conducted in similar climatic conditions. Mean temperature was 16°C and 14°C and relative humidity ranged from 40-75% and 45-90% for the trial plots and grass root experiment respectively. The densities of the treatments were similar but not the same which accounts for much of the difference between soils. Grass cutting heights were maintained at 12 mm for both experiments. The KL soil reached 22 % moisture content between two and four days whereas the OL soil took six days. Time to reach 22% moisture content increased with lower initial soil dry bulk density (Table 8.1).

Table 8.1 Days after soil saturation to optimum rolling gravimetric moisture content in mean (24 hour) ambient temperature of 14-16°C in the depth 0-60 mm for KL and OL soil.

Soil	Density (ρ_d) g cm^{-3}	25%	22%
KL	1.4	2	4
KL	1.6	0	2
OL	1.4	6	8
OL	1.6	0	6

These times relate to the 0-60 mm depth but variation within that depth will occur as drying will be faster closest to the soil surface. Times will also be reduced in climatic conditions more conducive to drying i.e. higher temperatures and greater wind speed.

In circumstances where pitches have been rolled previously and were initially at 1.60 g cm^{-3} dry bulk density before saturation the window of opportunity for rolling is relatively short. For the KL soil rolling within two days would be appropriate whereas with the OL soil rolling could be up to six days after saturation; although rolling at two to four days, albeit at a slightly higher moisture, may be more appropriate to ensure that the surface has not dried excessively. Soil with an initial dry bulk density of 1.40 g cm^{-3} will take considerably longer to dry delaying the optimum rolling time which could be beyond a practical point in terms of match preparation. These times would not be appropriate in spring as discussed previously but they illustrate the different drying properties of the soil types.

A tendency for soil drying during rolling was noted during some summer rolling experiments. This was not a statistically significant effect nor was it consistent in all experiments however it could be a result of roller/soil contact with a warm dry roller being in contact with the soil surface removing surface moisture.

Increase in dry bulk density can also result from soil shrinkage due to a reduction in soil moisture. Shrinkage will occur in all directions resulting in the formation of cracks at points of mechanical weakness. This results in soil between the cracks increasing in dry bulk density. The combination of reduced moisture content and shrinkage increases soil strength and hardness which results in an increase in pace and ball rebound (Adams *et al*, 2001; James *et al*, 2004). The increased incidence of cracks as soil moisture content reduces however may have a negative effect on rebound and pace consistency (Adams *et al*, 2004). A cracking-dry bulk density-moisture content relationship was developed and provides a basis for understanding target soil parameters for pitch preparation. A reduction in soil moisture content increases soil cracking in all compacted cricket soils, however lower moisture contents before cracking occurs can be tolerated by higher dry bulk density soils due to the lower void space available for shrinkage. Lower bulk density pitches after rolling will not be able to be dried to the same levels and therefore will not be able to achieve the same level of ball rebound.

8.3.2 Roller specifications

The rollers used in the field experiments, 725 kg m^{-1} and 920 kg m^{-1}, have been discussed in Section 5.4.1 in terms of their compactive potential. Roller mass above this was not examined in the field experiments however the DSIR (1951) determined that a roller of 2500 kg m^{-1} was required to increase dry bulk density in a sandy clay loam soil to 100% of Proctor optimum. This would entail a large increase in current roller mass at most UK cricket venues i.e. 2 drum 1.2 m wide roller would need to be 6000 kg. Roller mass and diameter was examined in more detail in the cricket rolling simulator experiments and is discussed in Chapter 7.

Every roller configuration will have a fixed maximum compactive potential and soil conditions will dictate whether this is achievable. Compactive stress is related to the roller mass and discussed in the conceptual model above. However in general terms the heavier the roller the greater the compactive force. The greater the soil dry bulk density and the lower the soil moisture, the greater the stress required to increase soil density. The choice of roller will therefore depend on soil physical conditions and initial and final soil dry bulk density.

For a groundsman to achieve the highest desired pitch dry bulk density the use of the roller with the largest compactive force/stress available will be required. The decision of whether to start with a lighter roller and gradually increase to a heavier roller as recommended (ECB, 2007) or go straight to the heaviest roller will largely depend on the initial and final dry bulk densities and moisture contents. Large differentials between these densities will be likely to cause roller indentation between rolled and unrolled soil due to the soil shear strength being exceeded at the roller edges; potentially resulting in undesirable permanent crease marks in the surface. In these circumstances it is likely that being prudent with initial roller weight would be appropriate (see Table 8.4; Reduction in surface height).

8.3.3 Roller passes

Repeated uniform loading of soil with fixed gravimetric moisture content has been shown to reduce the rate of soil compaction with successive loads (Chapter 4) and this is discussed in the conceptual model. For a soil dry bulk density below the compactive potential of a particular roller, the rate of increase in soil bulk density will reduce with successive roller passes until the roller potential dry bulk density is achieved with regard to the prevailing soil moisture conditions. The number of roller passes required to increase a soil dry bulk density to the roller's potential will depend on the differential between initial and end density and the soil moisture content.

Recommendations for roller passes have to exceed the optimum number to allow for the variability of the soil conditions which may be unknown by the groundsman. General guidelines have to cover a range of conditions rather than giving a list of options, as soil physical parameters may be unknown.

Guideline roller pass requirements, based on KL and OL soil tested experimentally at densities between 1.40 g cm^{-3} and 1.70 g cm^{-3}, are included in Section 8.4. These are calculated from experimental data (Section 8.2) derived from a mean increase of dry bulk density per roller pass of 0.015 g cm^{-3}. Change in dry bulk density was not determined from roller passes greater than those suggested in any of the rolling or soil mechanical property experiments.

The results indicate that correct rolling practice is different from current practice (Section 3.4.10). The majority of respondents in the survey of current practice roll substantially more than the experimental results indicate as being appropriate, offering considerable scope to reduce the time spent rolling at most cricket facilities.

8.3.4 Roller speed

The survey to assess current rolling practice (Chapter 3) determined a current average speed of 0.67 km h^{-1}, with only 8% of respondents rolling at speeds greater than 1 km h^{-1}. At speeds of 0.5 km h^{-1} to 1.0 km h^{-1} no measurable difference in dry bulk density occurred and therefore on the basis of field and experimental results, and the work of others, it would seem prudent to suggest a maximum speed of 1 km h^{-1} (i.e. at least 90 s to roll 25 m, assuming a roller length beyond the bowling crease at either end of the pitch) or additional passes may be required.

8.3.5 Grass roots

The root experiment determined that total rootmass in the 0-200 mm depth was not changed by increases in dry bulk density up to 1.77 g cm^{-3} for KL soil and 1.83 g cm^{-3} for OL soil, however changes in rootmass distribution did occur as a result of an increase in dry bulk density with roots reducing their depth of penetration and increasing rootmass higher in the soil profile. An increase in rootmass in the top 100 mm depth, resulting from an increase in soil dry bulk density, will increase the soil mechanical strength properties of a cricket pitch. Large reductions in rootmass between 50 mm and 100 mm could result in an abrupt change in shear strength which could be a cause of horizontal layering in pitches when subjected to rolling under certain soil moisture conditions. Rolling simulator experiments demonstrated the mechanical strength properties of grass roots and their resistance to horizontal strain. High or repeated horizontal stress on grass roots could cause root damage and this will be greater at higher levels of soil moisture.

Reduction of dry bulk density below 1.80 g cm^{-3} does not appear to be necessary to improve rooting into the compacted soil, however, changes in root depth and distribution as well as plant health may accrue from some form of decompaction. Reduced dry bulk density in the 0-100 mm depth resulted in an increase in rootmass immediately below 100 mm into the higher density soil compensating for reduction in depth of root penetration. Depth of decompaction is therefore an important consideration if considered necessary.

Penetration resistance (PR) in soils up to 1.80 g cm^{-3} was shown to reduce to < 3 MPa at winter soil moisture contents, (Section 5.4.6) allowing for the penetration of monocotyledonous roots although it was determined that root penetration would be restricted in low moisture conditions in high bulk density soils. Rootmass distribution changes also occurred as a result of dry bulk density change and could have occurred as a result of a PR below 3 MPa.

The majority of cricket pitches will only reach 1.80 g cm^{-3} dry bulk density as a result of shrinkage when dry. During winter rainfall, the expansion of these high density soils will reduce the dry bulk density to between 1.60 g cm^{-3} and 1.70 g cm^{-3} and therefore winter root penetration should not be greatly inhibited within the 0-150 mm depth, which is beyond the depth that is considered to affect pitch playability. Grass growth depends on light as well as temperature and varies between species. Slow growth is possible throughout the winter for perennial ryegrass (*Lolium perenne*) varieties however at air temperatures below 5°C grass plants are likely to cease respiration and leaf tissue growth and root growth will cease at soil temperatures of less than 0°C (North Carolina State University Turf Council, 2005; Taiz and Zeiger, 2002).

Furthermore root distribution changes caused by root inhibition could aid in pitch preparation due to the increase in strength and drying potential from a greater rootmass near to the surface. The necessity of roots penetrating below 100 mm has not been determined but as playability is considered to not be affected by soil physical conditions below 100 mm it seems unnecessary to remove moisture from that depth; and possibly concentrating moisture removal from the top 100 mm depth could be beneficial. However, shallow roots will reduce available water content for plant growth and increase plant stress which could have implications for plant disease and wear resistance.

Densities above 1.80 g cm^{-3} are likely to occur over time from soil consolidation due to overburden stress and are therefore likely to be at depths below 50 mm. Some form of decompaction may then become necessary if soil expansion does not reduce dry bulk density enough to allow for adequate rooting.

Soil type will influence the rootmass produced in the pitch profile with the KL type soil being less likely to require decompaction to encourage root growth. Further work needs to be undertaken to ascertain which cricket soils are more likely to reduce root growth but it is likely a lower median particle size (D_{50}) which reduces pore size, will result in reduced root activity rather than organic matter and dry bulk density as suggested by Baker *et al* (1998b) (Section 1.4.4.1).

8.3.6 Playability

The playability parameters of peak deceleration of the Clegg hammer and ball rebound were found to be strongly influenced by soil moisture content. This reduced their contribution to the assessment of rolling efficiency in conditions of changing moisture.

However the experiments were in general agreement with targets (ECB, 2004) for dry bulk density, moisture and ball rebound.

PR was influenced more by soil moisture than soil dry bulk density. Use of PR by groundsmen as an indicator of dry bulk density could therefore be misleading and not advisable as a means of determining the need for rolling. However when used as a measure of moisture content it may provide an intuitive feel, with experience, of the soil moisture conditions. Suggestions from the project sponsors for the development of a device that predicts the need for rolling will pose the problem that moisture and dry bulk density work in opposite directions with regard to soil PR and therefore separating the two parameters would be problematic.

8.4 Cricket pitch rolling draft guidelines

To provide guidelines to groundsmen it is important to understand their limitations with equipment, time or other resources, as well as the pitch performance that they should aspire to. This is discussed in Section 8.5 along with suggestions for dissemination of the knowledge gained from this research. This section gives an outline of research results appropriate for inclusion in guidelines for cricket pitch rolling.

8.4.1 General factors affecting rolling performance

Practical groundsmanship is looking for guidance in five principal areas of rolling management:

- When – timing of rolling; initial dry bulk density, soil moisture content (air voids) and soil type.
- What – roller specification; appropriate to achieve the desired outcome.
- How – the number of roller passes and the speed of operation required to achieve the desired outcome.
- Why – playability factors; target dry bulk density, moisture (match day) and ball rebound.
- Problems – grass roots, horizontal movement, root breaks and soil cracking.

8.4.1.1 Overwinter / initial dry bulk density

Spring pitch bulk density will depend on a number of factors but it will have reduced over winter due to soil expansion and other climatic and biotic affects. Autumn renovation will also have produced a lower bulk density surface for seed germination and many pitches will have been subjected to some form of mechanical aeration or decompaction. Dry bulk density reduction due to soil expansion could be considerable in the 0-50 mm depth but will be less at lower depths. The soil will increase in dry bulk density as it dries particularly at depths below 50 mm but early rolling will potentially reduce rewetting of the soil and encourage quicker natural recovery of soil bulk density.

8.4.1.2 Soil type

Soil type will affect the drying properties of the soil as well as the grass rooting environment. Significant differences were not determined between the high (OL) and low (KL) clay soils in terms of rolling management i.e. roller weight, speed and diameter, although final densities were slightly higher for the high clay soil. The benefits of lower clay soil are the speed of drying resulting in a more predictable management regime particularly in UK climatic conditions. Low clay soils also are likely to provide a healthier environment for grass roots. High clay soils have been shown to have greater strength in low moisture conditions and for this reason are preferred for pitches that will be used for matches played over a number of days and dried to low moisture contents. Low clay soils can however produce a higher level of playability at facilities with low levels of labour and pitch covering equipment.

8.4.1.3 Moisture

Moisture content is the key to rolling as well as the key to the final pitch condition. However the optimum moisture content for rolling is much higher than the optimum moisture for playability. Rolling requires adequate moisture to aid compaction but also a minimum of 2% air voids (and optimum voids of 5%) in the soil to enable soil particles to move closer together. The balance between moisture and air voids will depend on the soil dry bulk density as porosity (total soil voids) reduces as the soil becomes more dense (Table 8.2).

Table 8.2 Gravimetric moisture content at three levels of air voids (OL and KL soils; mean particle density (ρ_s) 2.65 g cm^{-3}.

	Dry bulk density g cm^{-3}						
Soil air voids	1.2	1.3	1.4	1.5	1.6	1.7	1.8
0% saturated	46	39	34	29	25	21	18
5%	42	35	30	26	22	18	15
10%	37	32	27	22	19	15	12
Field capacity moisture (%)	28	28	28	26	24	23	20
Field capacity air voids (%)	21	15	8	4	1	0	0

Ideally the groundsman will be able to assess soil moisture and dry bulk density to make an informed decision about the suitability of conditions for rolling (see Section 5.2.3; guidelines could incorporate a methodology for moisture and dry bulk density measurement). If this is not possible the field capacity air voids in Table 8.2 give an indication of air voids after 48 hours of drying after saturation for soils at different densities, however assumptions will have to be made regarding likely soil dry bulk density if no measurement is made.

Early spring rolling of pitches at field capacity will only be effective in low dry bulk density soils, up to 1.55 g cm^{-3}. After initial rolling densities will be likely to be close to this level and it is unlikely that further rolling will increase dry bulk density. To increase density further the soil will need to dry below field capacity which will only occur from evapotranspiration when climatic and grass growing conditions improve. Rolling once the soil has dried further will enable an increase in dry bulk density to a new level where air voids are once again reduced to below the minimum requirement or the roller has reached its compactive potential.

To achieve the maximum dry bulk density potential of a roller there is an optimum moisture content. For high dry bulk density targets (>1.50 g cm^{-3}) this can only be achieved after drying beyond field capacity. For low dry bulk density targets (<1.50 g cm^{-3}) the optimum moisture is close to field capacity. Rolling in optimum moisture conditions will also increase the soil density to a greater depth than if the soil is below the optimum moisture content. The optimum moisture will depend on the roller used and the dry bulk density that it can achieve and is discussed below.

The same moisture principles apply for summer rolling as in the spring although the process of drying happens much faster. Moisture optimums are reached within a shorter timeframe from saturation and rolling needs to take place within the correct time scale or the roller potential will not be reached. Rolling of pitches that are below the optimum moisture will not achieve the roller compactive potential regardless of how much rolling is done.

It is important to note that not all increases in bulk density are a result of rolling. Drying of the soil after rolling will increase dry bulk density through shrinkage and match day densities will invariably be greater than the final rolling density. Therefore capabilities of rollers discussed below refer only to the roller induced bulk density.

8.4.1.4 Roller Load

The potential for a roller to compact soil will be dependent on the roller weight and the contact of the roller drums with the soil. The easiest way to compare rollers is to divide the mass of the roller by the total width of all the roller drums gives you the roller mass per meter of roller drum (kg m^{-1}). Table 8.3 provides data on roller mass and the maximum dry bulk density that it can achieve if operated in the optimum soil moisture conditions.

Table 8.3 Roller compaction potential to 50 mm depth for a 600 mm diameter roller. Optimum gravimetric soil moisture content required to achieve maximum dry bulk density.

Roller mass kg m^{-1}	Roller equivalent: (2 drum; 1.2 m wide) kg	Maximum dry bulk density g cm^{-3}	Optimum moisture %	Percent of Proctor optimum density (ρ_d) %
260	650	1.26	27	75
440	1000	1.40	27	83
638	1500	1.50	25	89
750	1800	1.55	24	92
840	2000	1.58	23	94
920	2200	1.61	22	96
1250	3000	1.66	20	99

Each roller has a potential dry bulk density that it can reach and this cannot be improved with excessive use. It is much better to know the roller limitations and to optimise rolling efficiency to ensure that the rollers compactive potential is achieved.

The maximum dry bulk density achieved will reflect on the final playability characteristics of the pitch. Each level of cricket has different aspirations for playability and therefore roller selection should reflect this rather than inappropriate use of the wrong roller.

Potential damage caused by vertical shear at the edges of the roller (crease marks) will largely depend on the differential between initial pitch dry bulk density and the compactive potential of the roller in the prevailing soil conditions i.e. the final dry bulk density. Table 8.4 indicates the potential surface height drop (mm) resulting from a change in dry bulk density through rolling.

Table 8.4 Reduction in surface height resulting from rolling between an initial and final dry bulk density. Deduct initial density drop height (mm) from final density drop height to get actual drop in mm.

Reduction in surface height, mm

Initial dry bulk density, g cm^{-3}	Target dry bulk density, g cm^{-3} 1.2	1.3	1.4	1.5	1.6
1.2	0	4	7	10	13
1.3	-	0	3	7	9
1.4	-	-	0	3	6
1.5	-	-	-	0	3

When increasing dry bulk density from 1.50 g cm^{-3} to 1.60 g cm^{-3} the drop in height will be only 3 mm, which is unlikely to cause permanent pitch damage. If density was increased from 1.20 g cm^{-3} to 1.60 g cm^{-3} then drop in height could be as much as 13 mm, although this would require a number of roller passes. This would have a greater potential to cause damage and may benefit from density being increased in stages using a lighter roller. Whilst most facilities have limited choice of roller a lower weight at the start of rolling is likely to create less damage.

8.4.1.5 Diameter

Roller diameter influences the contact area of the roller with the soil and also the direction of pressure applied. Increasing the roller diameter will reduce pressure and compaction but it will also reduce horizontal soil movement i.e. roller bow waves. Increasing weight on the larger diameter roller to increase the dry bulk density potential is likely to increase the horizontal movement and reduce the advantage over a smaller diameter roller. Small roller diameters such as grass mower rollers will have a low compactive potential but a higher horizontal movement particularly in high moisture conditions. Differences in maximum horizontal movement were shown to be up to 49% less for a 1000 mm diameter compared to a standard 600 mm diameter roller in the depth 0-30 mm 840 kg m^{-1} (2 tonne; two drum; 1200 mm wide) roller and should be a consideration in purchase decisions.

8.4.1.6 Speed

Rolling speeds of 0.3 km h^{-1} to 1.0 km^{-1} do not have any difference in the eventual dry bulk density achieved from rolling. There is a possibility that the faster end of these speeds may reduce horizontal movement in high moisture conditions although this has not been verified at this present time. The suggested roller speed is approximately 0.7 km h^{-1} (i.e. 2 minutes to roll 25 m, assuming a roller length beyond the bowling crease at either end of the pitch). This is likely to approximate to most rollers operating in first gear at low engine revs. Reducing speed below 0.7 km h^{-1} will have no effect on the final dry bulk density achieved by the roller.

8.4.1.7 Roller passes

In general, increases in dry bulk density from rolling in a particular soil physical condition (moisture; dry bulk density) with a fixed roller specification will reach their maximum potential in six to seven passes of a roller drum. For a two drum roller this is three to four roller passes. This will be the case for most situations in soils of densities between 1.20 g cm^{-3} and 1.60 g cm^{-3}. In the spring this will bring the dry bulk density to a point of low air voids and therefore no further density increase can occur. General recommendations need to cover a wide range of early spring pitch conditions and so increasing the passes to 5 for a two drum roller would be prudent. Further drying, as previously mentioned, will allow for further compaction and a maximum of three to four further passes is all that is required to reach the air void or roller limit again.

Summer increases in dry bulk density following irrigation for pre-match pitch preparation (or prolonged heavy rain) require similar roller passes as the soil dries and it is best to split this over two days as the soil dries (Table 8.5).

Table 8.5 Roller passes required to achieve roller potential dry bulk density.

Reason for rolling	Roller passes
Spring, first rolling when dry enough	5
Spring, subsequent rolling per session. (Only when soil has reduced moisture content)	4
Pre match following saturation – 2 sessions of Further rolling for playability reasons only	5

Points to note:

- Continuous rolling beyond these recommendations has been shown to not increase soil dry bulk density any further.
- More rolling to compensate for incorrect timing of rolling will not achieve the roller compactive potential.
- Further rolling for pre-match preparation is at the discretion of the groundsman but should be considered for reasons other than increasing soil dry bulk density e.g. grass desiccation.
- Surface evenness will be improved by rolling but not beyond the recommended number of roller passes.

8.4.1.8 Problems associated with rolling

Rolling causes horizontal pressure in the soil that is resisted by the grass roots near to the soil surface. The amount of horizontal pressure increases as soil moisture and roller weight increase (or roller diameter reduces), thereby increasing the stress on the grass roots. Excessive stress on grass roots could cause horizontal root damage possibly leading to root breaks.

The implications for this are:

- Unnecessary increases the amount of stress which could lead to root damage.
- Rolling in high moisture soils increases horizontal stress; it is therefore advisable not to exceed roller pass recommendations particularly in high soil moisture conditions.
- Horizontal movement changes with soil moisture contents. It is important to ensure that moisture contents are as uniform as possible within the soil profile particularly in the summer after irrigation or after rainfall following a period of

drying. Rolling soil that has an abrupt change in soil moisture, with a wetter soil overlying a dry soil where moisture has not penetrated to depth, could cause horizontal shearing along the plane of moisture change.

- The common (and currently recommended; ECB, 2007) practice of 'flashing' of pitches to slow down pitch drying in hot weather should be considered with caution based on the preceding comments.

Note: Root-breaks can also be caused by factors other than rolling management e.g. incompatible soil used for topdressing and poor thatch management/control.

8.4.2 Spring rolling guidelines

The importance of soil moisture content to the effectiveness of spring rolling has already been discussed. No increase in dry bulk density will occur if the cricket square is rolled when there is too high moisture content although surface irregularities created since the end of the previous season rolling may be smoothed. Initial rolling can be undertaken after a minimum of 48 hours of dry weather but increase in dry bulk density will be small until soil drying increases later in the spring.

8.4.2.1 Roller weight

The practice of starting rolling with very light rollers (mowers) below 260 kg m^{-1} early in the spring has no benefit towards increasing pitch profile bulk density other than in very low dry bulk density pitches i.e. below 1.25 g cm^{-3} (see Table 8.3). Some sealing of the soil surface may occur reducing rain infiltration into the profile however any benefits will be limited and largely aesthetic.

Whilst soil moisture remains high, the limit to increasing dry bulk density is likely to be due to the moisture/density combination within the soil rather than the roller weight. Theoretically, a gradual increase in roller weight will result in the same final density as using the heaviest weight of roller throughout. Caution with roller weight is required to avoid surface damage, however, the roller with the final desired compactive potential should be used at the earliest opportunity to minimise the number of roller passes.

8.4.2.2 Passes

Guidelines for spring roller passes have to be a broad recommendation as circumstances are different from club to club in terms of dry bulk density and soil moisture. No more than five roller passes would be beneficial at any one moisture content/roller weight combination. After the initial rolling in spring, at least one further rolling session of 4/5 roller passes could be productive if soil moisture has reduced. Further rolling will only increase dry bulk density if the roller used has not reached its compactive potential and the soil moisture is close to optimum.

Although spring rolling has an important effect on pitch bulk density, the main benefit is reducing overall moisture holding capacity of the soil so that the pitch profile is ready for match preparation when the playing season begins.

Playing seasons that start early, before vigorous grass growth, will need to use pitch covers to aid in the reduction of soil moisture, although the drying process will be slow due to low early season temperatures and high humidity under the covers.

8.4.3 Summer pitch preparation

Summer pitch reparation follows the same rolling principles as spring rolling but drying rates are quicker and therefore timing is more crucial. All the principles discussed above for general rolling guidelines and spring guidelines are important for pre-match summer rolling.

8.4.3.1 Playability aspirations

Targeted playability will dictate rolling parameters, in particular roller weight and optimum moisture. Suggested targets by performance level presented in Table 8.6 also indicate required roller specification to achieve the targets. Minimum moisture for match day conditions is based on the likely incidence of cracking and is therefore a guideline which should be monitored by groundsmen. Further drying is likely to increase ball rebound but reduce consistency as cracking increases.

Table 8.6 Target rolling and match day dry bulk density and soil moisture by level of performance.

	Rolling conditions			**Match day conditions**			
	Rolling density (ρ_d)	Roller mass	Rolling moisture	Dry bulk density (ρ_d)	Minimum moisture	Ball rebound	Clegg (0.5 kg)
Performance level	g cm^{-3}	kg m^{-1}	θ_m%	g cm^{-3}	θ_m%	%	g
First class	1.60	920	22	1.65 -1.70	18-16	20-25	400+
Club (high performance)	1.55	750	24	1.60	19	15-20	370
Club (medium performance)	1.50	640	26	1.58	20	10-15	340
Club (lower performance)	1.45	500	27	1.52	21	10	300

As roller choice is usually limited, pitch dry bulk density will be dictated by the available roller. However manipulation of playability by moisture content could lead to inconsistent ball rebound and therefore use of the correct roller for the desired playability should be the long term goal of all cricket facilities.

8.4.3.2 Timing and moisture content

Initial dry bulk density will vary according to facility and if any spring rolling or previous match preparation has taken place; rolling a previously used pitch later in the season will still follow the same principles.

Moisture content may be below optimum for rolling and will therefore need to be increased through irrigation over a period of time that enables as close to saturation to a depth of 100 mm as is possible. If soil moisture content is not increased the maximum compactive potential of the roller will not be achieved (regardless of the number of roller passes).

Rolling at the optimum moisture content is crucial to optimising roller compactive potential. If accurate measurement of moisture is not possible Tables 8.7 and 8.8 provide a guide as to moisture content for days after saturation of the pitch profile. These are based on mid summer temperatures (mean 24 hour temp 16°C) and could vary considerably with climatic conditions.

Table 8.7 Approximate moisture content for 0-50 mm depth for days after pitch saturation in a low clay soil resulting from good mid-summer drying conditions.

Low clay (25%)

Days after saturation	**Dry bulk Density**			
	1.4 g cm^{-3}	**1.6 g cm^{-3}**	**1.7 g cm^{-3}**	**1.8 g cm^{-3}**
1	32	25	21	19
2	28	23	21	19
3	23	21	20	19
4	22	20	19	18
5	21	19	18	16
6	20	18	17	15
7	18	17	16	14
8	17	16	15	13
9	16	16	14	11
10	16	15	13	10
11	15	15	12	9
12	15	15	11	8
13	15	15	9	8
14	14	15	8	7
15	14	14	7	6

Table 8.8 Approximate moisture content for 0-50 mm depth for days after pitch saturation in a high clay soil resulting from good mid-summer drying conditions.

High clay (30%)

Days after saturation	**Dry bulk density**			
	1.4 g cm^{-3}	**1.6 g cm^{-3}**	**1.7 g cm^{-3}**	**1.8 g cm^{-3}**
1	33	26	22	20
2	32	25	20	19
3	31	25	18	18
4	29	24	18	18
5	27	23	17	17
6	26	22	17	17
7	24	21	16	16
8	23	20	16	16
9	21	19	15	15
10	20	18	14	14
11	19	17	13	13
12	18	16	12	12
13	17	16	11	10
14	16	15	10	9
15	15	14	9	8

The tables indicate the low clay soil is at optimum moisture after 48 hours of drying for most dry bulk density levels whereas the high clay soil takes longer to reach the optimum moisture (5-6 days). If the pitch dry bulk density is not known but it has received some spring rolling it should be assumed that the pitch is at the 1.4 g cm^{-3} dry bulk density level after irrigation.

These tables also provide a guideline number of days for drying to a required moisture content for match day. For example a club medium performance requirement of 20% (Table 8.6) match day moisture content will occur at approximately four days after saturation on low clay soils and eight days on high clay soil.

8.4.3.3 Passes

Summer pre-match rolling requires a maximum of 10 roller passes (two drum roller) to achieve the roller compactive potential. With low clay soil this should be done in the period 36 to 56 hours after saturation in one or two sessions and with the maximum roller weight for at least six of these passes. After this time the full compactive potential of the roller will not be achieved.

For the high clay soil, the drying to optimum moisture content time is more likely to be influenced by the ambient weather conditions. However the following regime with a two drum roller is suggested:

- An initial rolling of two roller passes within 48 to 72 hours preferably with the maximum roller weight but with regard to potential damage, which will depend on the initial pitch dry bulk density.
- A further four roller passes per day for the next two days should be sufficient to achieve maximum potential.
- A total of 10 roller passes with at least the last six roller passes with the maximum roller weight.
- The timings of these will change according to the weather conditions however it is important not to leave rolling until the soil has dried below the optimum.

Further rolling beyond the recommended 10 roller passes is unlikely to increase pitch dry bulk density and for reasons discussed previously should be only undertaken for other playability reasons. For this purpose it would be prudent to consider using a much lighter roller to prevent excessive horizontal soil stress.

8.5 Management considerations

8.5.1 Introduction

The optimisation of cricket pitch rolling was seen by the ECB as part of their overall strategy to achieve their goals (ECB, 2005). An improved scientific understanding of rolling of cricket soils can potentially provide groundsmen with a more informed understanding of the potential and limitations of their roller and help them to achieve a more consistent standard of playing surface. However the effectiveness of this research in helping to achieve improved standards throughout the game will only become clear in future years when the recommendations of this work have been fully disseminated. Different levels of cricket have different expectations for pitch performance and therefore guidelines generated from this research will need to be appropriate to all facilities.

Economic and environmental benefits accruing to the sport of cricket from this study are potentially substantial should a fundamental change in the attitude towards rolling occur. Research findings indicate that much time is wasted from rolling pitches without an increase in soil dry bulk density; this could result in labour cost or allocation savings and reduced fuel cost and CO_2 emissions.

The survey of current rolling practice highlighted the variation between groundsmen and facility types in rolling practice and provides a benchmark for future assessment and will also provide the opportunity for a financial assessment of the success of this project.

8.5.2 Pitch performance and safety

Consistency of pitch performance, both in terms of pitch to pitch and within a pitch, is important for encouraging participation and also providing a playing surface that is likely to create the desired levels of entertainment.

Inconsistent ball rebound is considered to have implications for player safety as well as being difficult for players at all levels to realise their run scoring potential. Both of these factors can reduce participation, particularly at the lower end of the game and from newcomers to the game. Player skill is developed over many years and learning to play cricket on a wide range of playing surface types could enhance a player's skill. Low scoring matches though, are not considered a good spectacle for followers or the media and this is the main justification for consistency in the first class sector. It could be argued that inconsistent pitch performance is generally equal for both teams and should not lead to a team being any less successful than its opponents in the long term, albeit a greater element of luck could influence some games. However, advantage could accrue to the home team through the course of a season as players are more used to playing on a particular surface type; for this reason pitch standards are monitored by the ECB.

Even dry bulk density and soil moisture content together with a pitch profile that has no structural weaknesses (horizontal layering) are the key factors to consistent ball rebound. Rolling of soil outside the limits of optimum moisture content and roller passes set out in the guidelines could result in uneven bulk density and drying, excessive drying could lead to cracking and unstable playing surfaces and rolling in inappropriate soil moisture conditions could cause layering, all of which could lead to inconsistent ball rebound.

8.5.3 Performance and expectations

Standards and expectations of pitch performance will vary throughout the game. Factors determining performance again largely relate to soil moisture and dry bulk density, but soil density is also dependent on available roller specifications.

Dry bulk density and moisture targets for pace and ball rebound performance have previously been aimed at the first class game which may be inappropriate for school or club cricket. Guidelines resulting from this work will need to categorise recommendations according to facility type to ensure all levels of the game get appropriate advice and performance targets.

Available roller type and specification varies widely across all facilities and guidelines should be clear as to the potential performance of specific roller weights in terms of pitch preparation and playability. The purchase of new rollers could be influenced by the guidelines and it is important to stress the consequences of increasing roller size i.e. roller weight and drum dimensions, and justification of roller purchase should not be made on the basis of unsuitable playability targets.

8.5.4 Financial and environmental benefits

The results of the rolling study compared to the current rolling practice survey suggest that most groundsmen will be able to reduce considerably the time spent rolling, for both spring rolling and pre-match pitch preparation. An improved understanding of rolling by groundsmen could lead to a large reduction of unnecessary rolling that is currently occurring as a result of rolling at incorrect soil moisture content or rolling beyond the rollers compactive potential. This will lead to cost savings in terms of labour and fuel at all facilities. Although much of the labour is voluntary at lower levels of the game this does at least allow for a reallocation of labour to more productive tasks. Fuel cost savings across the whole of the cricket sector could be substantial should the rolling recommendations become standard practice (Table 8.9). Uptake of recommendations should therefore be justifiable on financial as well as an environmental basis at both facility and national level.

Table 8.9 Potential time, cost and CO_2 savings from a change in rolling practice for spring and pre-match rolling. Relatively small savings for each facility become potentially large savings for the whole cricket industry.

	Current practice			Recommended		Cost and time saving per season					
Spring rolling						**Per facility**			**National saving**		
	Time/pitch	Pitches	Time/ Square	Time at 0.7 km h^{-1}		Time	Fuel. 1 litre h^{-1}	Facilities	Time	Fuel	CO_2
	Hours	no.	Hours	Hours		Hours	£	n	Hours	£	kg
First class	2.5	19	48	20.4		27.6	16.6	18	498	299	256
Clubs	2.3	13	30	13.9		16.1	9.6	5000	79,857	47,914	41,046
Schools	1.9	10	19	10.7		8.3	5.0	1500	12,429	7,457	6,388
Total - Spring rolling									92,783	55,670	47,690
Summer pitch preparation						**Per facility**			**National saving**		
	Time/pitch	Matches	Time per season	Time/ match	Time/ season	Time	Fuel		Time	Fuel	CO_2
	Hours	no.	Hours	Hours	Hours	Hours	£		Hours	£	kg
First class	6.4	45	288	2.2	99	190	114	18	3,420	2,052	1,758
Clubs	3.3	56	185	2.2	123	62	37	5000	310,000	185,000	159,340
Schools	7	50	350	2.2	110	240	144	1500	360,000	216,000	185,040
Total - Summer rolling									673,420	404,052	346,138
Total all season rolling									766,203	459,722	393,828

Assumptions made in the calculation of cost and time savings in Table 8.9:

- Recommended rolling - 15 passes in the spring; 15 passes pre-match.
- Recommended pre-match rolling doubled to allow for non compaction rolling (e.g. grass desiccation).
- Fuel price @£0.60 per litre.
- Fuel usage @ 1 litre per hour (based on a Kubota D722 3 cylinder diesel engine[6]).
- CO_2; calorific value of diesel fuel = 0.514 kg CO_2 released per litre of fuel used
- Facilities: 18 first class grounds; 5000 clubs; 1500 municipal facilities.
- Current practice is a mean from the groundsman survey and therefore a particular facilities savings will be dependent on current practice.

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[6] Personal communication received from Trevor Luckhurst, Poweroll Precision and Fabrication Ltd, Gunnislake, Cornwall. UK.

Municipal facilities where contract rolling costs are incurred could gain substantial financial benefits for funding bodies (Table 8.10).

Table 8.10 Potential cost savings for a contract rolled facility cricket square.

Facility	Pitches	Current	Recommended	Time, cost and CO_2 saving		
Contract rolling	no.	Hours	Hours	Hours	£	CO_2; kg
Spring rolling	10	19	11	8	160	4
Pre-match rolling	50	175	110	65	1,300	33
Total saving per facility				73	1,460	37

Assumptions made for the calculation of Table 8.10:

- Contract price £20 per hour. Rates vary a great deal and will also be dependent on roller availability.
- CO_2; calorific value of diesel fuel = 0.514 kg CO_2 released per litre of fuel used.
- Recommended rolling - 15 passes in the spring; 15 passes pre-match.
- Recommended pre-match rolling doubled to allow for non compaction rolling.
- 10 pitch square; 50 pitches prepared per season; rolling speed 0.7 km h^{-1}.

Although calculations in Tables 8.9 and 8.10 make a number of assumptions that could be subject to change as well as the assumption that reductions in rolling times will become standard practice, there is a clear indication that the results of this project can provide cost saving benefits to all facilities individually and to the industry as a whole. This justifies the financial commitment to the project by the ECB and it also should provide the sponsors with evidence of their commitment to environmental awareness.

8.5.5 Future assessment of project impact

Survey data from the project provides a benchmark of current practice as at spring 2006 and future assessment of groundsman practice will be able to use this data for comparison.

Preliminary research findings have been presented to a number of different groundsmen audiences and the feedback, although limited, has been positive. To assess the impact on pitch preparation, both in terms of pitch performance and cost and time savings, will require at least 12 months after the formal guidelines are published (this is targeted for

February 2009; see Section 8.5.6) to allow for all groundsmen to have the opportunity to receive the information. However a preliminary survey is currently being undertaken by Cranfield University as part of a cricket pitch aeration study[7]. Attempts at assessing improvements in participation, safety, enjoyment and spectator following are unlikely to be conclusive as they are subject to a range of different influences however the groundsman survey could be expanded to include questions on changes in strategy and improvements, or otherwise, as a result.

8.5.6 Dissemination of guidelines

The main purpose of this research, from the sponsor's perspective, was to provide cricket groundsmen with an improved understanding of roller use in the preparation of cricket pitches. It is therefore important that the knowledge gained is disseminated to groundsmen at all levels as effectively as possible. It is also important that this knowledge is either targeted at a particular level which could require four different guidelines (first class, club, school and municipal/contract) or guidelines which provide categorised recommendations. The latter would provide a cheaper and more manageable approach.

Approach to dissemination should incorporate the following:

- Hard copy guidelines to be distributed to CGA's (County Groundsmans Associations) and county pitch advisers.
- Presentations at all levels to encourage awareness and interest in the guidelines.
- Particular attention should be given to trying to involve those that are responsible for municipal and school facilities as the guidelines are likely to benefit these facilities at least as much as those higher up the cricket ladder.
- Workshops aimed at different levels with the chance for groundsmen to discuss their own circumstances. Also potential for pitch advisor training workshops.

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[7] Aeration of cricket pitches. Simon Parsons, EngD Research Engineer. Centre for Sports Surface Technology, Cranfield University

- Online availability of guidelines. The rolling survey had 51% of respondents using the internet option. Increasing use of this medium for communication between groundsmen would indicate that it is a cost effective method of distribution of information.
- Interactive web page – Cranfield / ECB, i.e. opportunities for groundsmen to input roller weights / moisture contents to get guideline output on dry bulk density targets / roller passes / playability expectancy and soil parameters to get air voids. This would provide a link with groundsmen and could be developed for future research dissemination and knowledge updates away from the commercial websites.
- Video of a presentation on the main project results and how they can be put into place in a facilities rolling management regime. This could be available for use at presentations given by those less familiar with the research or as part of the training workshops.
- Guidelines could form the basis of a 'standard' pitch preparation protocol for municipal or contract maintained facilities to ensure uniformity of preparation at lower levels of the game.

Current plans include a launch of the guidelines in spring 2009 at the IOG Groundsmans' Conference in time for the beginning of the 2009 cricket season.

8.5.7 Project delivery

The project was conducted over a period of four years and two months. Time over run by two months was a result of mitigating circumstances beyond the control of the project, in particular the move of most of the Silsoe staff and facilities to the Cranfield campus.

Financial restrictions were adhered to and final costs were on budget (Appendix 12). Delivery of the cricket rolling guidelines to the cricket industry was outside of the project remit.

Chapter 9. Conclusions and contribution

The aim of the research was to develop an improved understanding of the compaction of cricket soils under a dynamic compressive load in order to provide practical strategies and guidelines for the optimisation of cricket pitch compaction. To achieve this aim this thesis sets out a number of objectives (Section 2.4) to which the following section, contribution to knowledge, research limitations and recommendations for future study and the research conclusions are aligned.

9.1 Conclusions

1. Current cricket pitch rolling management was determined through a survey of UK based cricket groundsmen. 120 questionnaire respondents provided a valid statistical analysis of the first class and club cricket sectors but a low number of returns from the school and municipal sectors reduce the sectors results validity. Results indicated wide variations in management protocols for spring rolling and pre-match rolling, in particular the timing and time spent rolling and equipment availability, both between all facilities and between facility types. Roller passes for spring compaction ranged from 5 to 280 and 3 to 325 and for pre-match summer rolling from 35 to 236 and 5 to 540 for first class and club respondents respectively. Roller mass used for spring rolling ranged from 255 kg m^{-1} in early spring to 773 kg m^{-1} in late spring across all facilities. Rolling equipment used for summer pitch preparation ranged from 500 kg m^{-1} to 1000 kg m^{-1} for all facilities and 100 kg m^{-1} to 1250 kg m^{-1} for match day preparation. Roller speed was determined to have an overall mean speed of 0.67 km h^{-1} (ranging from 0.3 to 3.4 km h^{-1}) across all respondent data.

Survey returns also provided benchmark data for cricket pitch management including pitch construction and soil use, techniques used in rolling practice and pre-match irrigation and rolling, all of which informed project experimental design.

2. Mechanical properties of two soils (Ongar loam and Kettering loam) were determined. Standard Proctor tests (2.5 kg rammer) indicated optimum dry bulk density was 1.68 g cm^{-3} at an optimum gravimetric moisture content of 19.1% and the modified Proctor test (4.5 kg rammer) indicated 1.86 g cm^{-3} dry bulk density at 14.3% moisture content. No statistical difference was determined between soils. Air voids at the optimum density were 3.5% and 5% for the two Proctor tests. Triaxial shear strength experiments indicated a significant** decline in strength from 123.9 kN m^{-2} to 41.9 kN m^{-2} with an increase in gravimetric moisture content from 8% to 23%, although there was no significant change between 8% and 15% mainly due to the increase in soil cohesion. Decline in strength was largely attributable to a reduction in friction (ϕ) from 51.8° to 5.9°, rather than a change in soil cohesion which increased significantly between 8% and 15% moisture content from 0.1 kN m^{-2} to 30.8 kN m^{-2} and then remained statistically stable to 23% moisture content.

Changes in moisture content were also determined to influence strength and stiffness in dynamic triaxial experiments. Elastic and plastic strain increased with an increase in soil moisture content from samples with 16%, 20% and 25% gravimetric moisture content and reduced with an increase in dry bulk density for samples of 1.20, 1.40 and 1.60 g cm^{-3} density in OL soil. Soil strength and stiffness increased as a result of a reduction in soil moisture content as well as with an increase in soil dry bulk density. Stiffness also increases with successive loads as soil bulk density increases. Stiffness parameters were calculated and indicated a mean stiffness of 97.38 MPa, 30.16 MPa and 10.51 MPa for moisture contents of 15%, 20% and 25% respectively for a soil dry bulk density of 1.60 g cm^{-3}. Stiffness of 16.26 MPa was determined for a soil dry bulk density of 1.40 g cm^{-3} at 20% moisture content.

Repeated soil loading with a constant load using triaxial apparatus indicated declining increases in dry bulk density with successive loadings due to increases in shear strength and soil stiffness that resulted from the increase in soil density. Rolling soil with a smooth wheeled roller in laboratory conditions also determined a decline in density increase with successive roller passes with a maximum soil dry bulk density achieved after 10 roller passes on OL soil with an initial density of 1.10 g cm^{-3}. Densities of 1.36 g cm^{-3} and 1.46 g cm^{-3} were achieved for soil at 20% gravimetric moisture content using a 403 kg m^{-1} and a 638 kg m^{-1} roller respectively, to a depth of 50 mm.

Soils with higher strength were determined to require greater load stress to increase dry bulk density. A soil-specific relationship between minimum load stress, dry bulk density and gravimetric moisture content appropriate to cricket pitch rolling was established which indicated substantially higher levels of pressure were required to increase dry bulk density than the maximum stress at failure derived from shear tests. For a soil with a dry bulk density of 1.60 g cm^{-3} a minimum load stress for compaction was determined to be 88 kPa, 260 kPa and 566 kPa for OL soil with gravimetric moisture contents of 25%, 20% and 15% respectively.

3. Reductions in pressure required for compaction as a result of an increase in moisture were demonstrated in laboratory and simulator experiments. An increase in soil moisture reduces the compactive force required to compact soil due to the reduction in soil friction. This occurs only to the point where soil strength increases as a result of low levels of compressible air voids and soil stiffness increase due to the incompressibility of water. Optimum moisture at 5% air voids for maximum densities achieved in field experiments were 24% for the 750 kg m^{-1} roller and 22% for the 920 kg m^{-1} roller.

Optimum soil physical conditions for rolling depend on the roller compactive potential. Proctor optimum moisture is only relevant for a roller that has the potential to reach the Proctor optimum dry bulk density. Optimum moisture for compaction has been derived from the assumption of 5% air voids for a range of roller weights.

4. Rolling protocols were developed for spring and pre-match rolling.

Dry bulk density and roller mass. Maximum soil dry bulk density was determined to be defined by a rollers contact pressure in conjunction with appropriate optimum soil moisture content resulting in a specific compaction potential. Compactive potential was not achieved if soil moisture content was above or below the optimum. Maximum dry bulk densities achieved for a 750 kg m^{-1} (standard un-ballasted cricket roller) were 1.55 g cm^{-3} and for a 920 kg m^{-1} roller (ballasted standard cricket roller) 1.61 g cm^{-3} which was 92% and 96% of the standard Proctor optimum density. These were for depths of 0-30 mm. In the depth 30-60 mm 90% of Proctor optimum (1.51 g cm^{-3}) was achieved with rolling, although in most cases the soil was naturally at this dry bulk density. A range of maximum densities for different roller masses were determined in different moisture conditions enabling the production of guidelines on roller compactive potential for cricket rollers with masses from 250 to 1250 kg m^{-1}.

Roller passes. Rate of dry bulk density increase reduced with consecutive load or roller passes in all experiments. Field and simulator experiments determined a mean roller dry bulk density increase per roller pass of 0.015 g cm^{-3} (two drum roller) although rates of compaction altered with roller weight and soil density from 0.0018 to 0.035 g cm^{-3}. Regardless of roller weight or soil physical conditions all soil dry bulk density increase was achieved after seven roller (single drum) passes and 98% of final density was achieved after three passes of a two drum roller.

Diameter. Roller diameter affects soil/roller contact area and contact angle. An increase in roller diameter from 600 mm to 1000 mm reduced contact pressure due to the increase in roller soil contact. An increase in roller diameter also reduces contact angle and the direction of pressure. Larger diameter rollers will reduce compactive potential; however, the reduction in contact angle reduces horizontal soil movement which was shown to be up to 49% less for a diameter of 1000 mm compared to a 600 mm roller for a 1250 kg m^{-1} roller in soils with 20% moisture content.

Speed. Rolling speeds were compared (0.3 to 0.6, 0.45 to 0.9 and 1.0 to 2.0 km h^{-1}) and no difference in the eventual dry bulk density achieved from rolling speed was determined. The project hypothesis that an increase in roller speed will reduce the increase in dry bulk density is therefore rejected. The guideline roller speed range is 0.3 to 1.0 km h^{-1} which aligns with current practice.

Moisture. Optimum moisture was determined for a range of roller weights (Conclusion 3). Soil drying times were measured and provide a basic tool for pitch preparation.

Playability. Linear regression models for Clegg hammer and ball rebound were found to be strongly influenced by soil moisture content. This reduced their contribution to the assessment of rolling efficiency in conditions of changing moisture. A relationship between ball rebound and soil cracking was developed using the soil parameters of moisture and dry bulk density. Ball rebound of 18% was predicted to occur at 378 G at the target dry bulk density of 1.65 g cm^{-3} and at 19% moisture content.

5. The grass rooting experiment determined that an increase in dry bulk density of KL soil up to 1.77 g cm^{-3} and OL soil up to 1.83 g cm^{-3} did not change total rootmass in the top 200 mm of the soil profile; although rootmass distribution was altered by an increase in dry bulk density resulting in an increase in root growth closer to the soil surface and a reduction in root depth. Reducing soil dry bulk density in the top 100 mm of the soil profile stimulated a plant response of an increase in rootmass immediately below the 100 mm depth; this was particularly the case for a soil with a dry bulk density of 1.60 g cm^{-3} overlying a soil of 1.80 g cm^{-3} dry bulk density.

Rooting depth and distribution was influenced by soil type. Total Rootmass in the 0-200 mm depth was greater for KL soil at all densities and at all depths compared to the OL soil. At the same time OL soil had a greater percentage of the total rootmass in the 0-50 mm depth. This was explained by the different particle size distribution of the two soils which had a median particle size (D_{50}) for KL soil of 45 µm compared to the OL D_{50} of 11 µm. The larger particle size resulted in greater variation in pore size offering less rooting impedance and greater drainage and therefore greater air-filled porosity.

Although soil bulk density is a factor in root growth the soil moisture content has the most influence on root penetration. A penetration resistance (PR) model determined that soil moisture explained 76% of the variation in PR, which was in agreement with other work. In OL and KL soil a PR of > 3 MPa occurred for 1.80 g cm^{-3} and 1.70 g cm^{-3} dry bulk density soil with gravimetric moisture content below 18% and for densities of 1.60 g cm^{-3} and 1.50 g cm^{-3} below 17% moisture content. This had previously been determined by other work to be the point of root inhibition in monocotyledonous plants. It can be concluded that in cricket pitches a reduction in root penetration will occur should moisture content fall below these levels. However winter moisture content will be above these levels and should allow for adequate root growth in high bulk density cricket soils although some change in root distribution could occur. This may reduce available water content and increase plant stress which could have implications for plant disease and wear resistance.

The increase in shear strength resulting from grass roots in the soil profile was demonstrated with the shear vane results indicating a significant increase in strength for soil at 0-30 mm depth compared to the depth 30-90 mm for moisture contents between 20% and 32% gravimetric moisture content.

6. Roller dynamic forces that occur during rolling were influenced by soil moisture. Soil moisture experiments determined a reduction in soil stiffness with an increase in soil moisture increasing the potential to increase dry bulk density with a given load.

Lower soil moisture content increased soil strength and stiffness, with lower plastic strain reducing soil compaction.

A higher level of soil moisture increased roller sinkage as a result of reduced soil strength which increased the roller contact area reducing surface pressure. Lower moisture content reduces contact area resulting in higher surface pressure and a higher dry bulk density on the surface of a pitch but with less density at lower depths.

Pressure distribution through the soil declined with depth more rapidly for lower moisture contents. Pressure duration was also longer for lower moisture content. However despite a lower pressure applied for a shorter duration a higher moisture content soil increased dry bulk density to a higher level at lower depths due to the lower force required to compact soils.

The initial roller pass expends energy in compacting soil closest to the roller/soil contact reducing pressure at lower depths. Subsequent roller passes resulted in greater pressure at lower depths with a consequential increase in soil dry bulk density.

Soil marker movement indicated increased soil movement for higher moisture content resulting in an increased horizontal and vertical strain. Grass roots reduced horizontal soil movement by resisting the horizontal stress. Grass root orientation is generally vertical and therefore reinforces the rootzone against horizontal stress. The effect on vertical deformation is lower due to the compressibility of roots. Differences in horizontal movement between soils of different soil moisture content could cause horizontal shearing between soils that have an abrupt change in soil moisture content with depth.

It was shown that soil strength and stiffness is increased with grass roots increasing the force required to compact the soil. Predictions of attainable dry bulk density based on soil only profiles may therefore overestimate achievable density with a particular roller configuration.

The increase in roller/soil contact resulting from a larger roller diameter reduced contact pressure and showed a tendency to reduce dry bulk density at depths to 90 mm. Horizontal elastic and permanent strain was reduced with the 1000 mm roller due to a smaller soil/roller contact angle.

7. Guidelines for the use of a smooth-wheeled roller for the rolling of cricket pitches in spring and pre-match rolling have been developed from experimental results. These include information on the timing of roller use with regard to soil moisture, the selection of roller specification for the desired increase in soil dry bulk density as well as the final pitch performance; the operation of the roller with regard to speed and roller passes is also included. Suggestions have also been made as to how use of rollers in inappropriate moisture conditions could result in damage to the pitch profile and therefore how to avoid this. A proposal for the dissemination of guidelines to cricket groundsmen has been presented which could include an ECB standard protocol for contract managed pitches.

8a. The results of this thesis will present cricket groundsmen at all levels of the game with an improved understanding of the effective use of a roller providing the opportunity to produce more consistent playing surfaces. Facilities should be able to plan their rolling strategies to produce playing surfaces which align with their playing aspirations. This will encourage individual player performance which could lead to greater participation at the lower levels of cricket and improved entertainment throughout the game.

Effective rolling practice and an improved understanding of pitch drying should improve consistency of surface playability and improve pitch safety resulting from erratic ball trajectory. This is caused by uneven dry bulk density and moisture and the breaking up of surfaces and pitch cracking.

Conclusions relating to potential pitch profile damage from horizontal soil movement could reduce the incidence of horizontal layering in pitches which reduce ball pace and rebound consistency. These occur at all levels of the game and often result in the need for expensive pitch renovations to rectify the poor playability performance.

Results from experimental work indicate that different rolling strategies may be appropriate to different levels of play within the sport. Proposals have been suggested for aiming guidelines at level of performance to enhance all levels of the game whilst respecting the standard of performance required. This will enhance individual satisfaction and performance and encourage continued participation.

8b. A basic cost analysis determined potential time savings of 218 and 78 hours for first class facilities and clubs respectively with a potential for 766,000 hours of time saved for all UK facilities. An assessment of fuel savings indicated potential annual savings of £130 for first class and £53 for clubs. Across the industry this could amount to in excess of £460,000. This equates to a reduction of 394,000 kg of CO_2 emissions.

Impact of this thesis, the research findings and the guideline dissemination will only be possible after at least a 12 month period and will need to be assessed by further groundsman surveys.

9.2 Contribution to knowledge

1. Survey of cricket groundsmen provided data on current rolling management practice which had not previously been assessed on a UK wide basis. This provides benchmark data for cricket rolling management enabling future assessment of uptake and benefits resulting from recommendations from this and future work. It also provides the ECB with an informed understanding of where weaknesses lie in funding and knowledge within the groundsmen sector of the cricket industry enabling future targeting of funding and training.

2. Mechanical characterisation of compacted cricket loam soils with a range of dry bulk density and moisture combinations. Determination of minimum stress for compaction of cricket loams using triaxial equipment.

3. Determination of optimum air voids and evaluation of optimum air voids from other work to obtain optimum moisture content for compaction of clay loam soil. Optimum moisture has been derived for a range of smooth-wheeled roller weights.

4. Protocols for cricket pitch rolling have been developed to maximise dry bulk density from a particular roller specification. This utilises experimental results and existing soil water and mechanical knowledge. Increased knowledge of the relationship between moisture, dry bulk density and roller mass and the influence on pitch playability will enhance the groundsman's ability to produce the desired pitch playability characteristics.

5. The grass rooting experiment increased the knowledge of the effect of grass roots growing into compacted cricket soils. Only limited previous work has been carried out for grass root distribution into cricket pitch soils.

The results identify the change in root growth from different soil particle distribution and the change in root distribution as roots encounter different bulk density soils.

6. Cricket rolling simulator developed a new methodology for measuring soil movement under a dynamic load, through simulator design and software development. A number of other contributions to knowledge were made:

- Data was produced demonstrating differences between vertical and horizontal strain in soils with different moisture contents.
- Pressure distribution under a moving roller in different moisture, speed and roller diameter scenarios provides a greater understanding of the influence of moisture and roller configuration on soil movement and compaction.
- The extent to which soil moisture influences soil horizontal movement was measured which could have significant implications for the preparation of cricket pitches.
- It was determined that a reduction in the soil roller contact angle resulting from a larger diameter will reduce the horizontal pressure in favour of an increase in vertical pressure.
- The reinforcing behaviour of grass roots in the soil profile was quantified.

7. Groundsman guidelines increase the knowledge available to the cricket industry for preparation of cricket pitches at all levels of the game.

8. This thesis will make a valuable contribution to the Sponsor's business objectives.

9.3 Research limitations and recommendations for future study

1. Questionnaire returns were well distributed between clubs and first class facilities however not enough emphasis was put into the surveying of schools and municipal facilities. With these facilities being the basis for youth cricket development it is important to ensure that these facilities receive the same level of focus, if not more, on pitch management and performance as facilities that are at a higher level in the game.

Future work should include follow up surveys to evaluate the uptake of knowledge gained and disseminated from this project and this should involve a greater emphasis on school and municipal facilities.

2. Characterisation of soil mechanical properties was carried out for two soils. At least 20 cricket soils are commercially available and could present different results. The chosen soils were at either end of the available soils scale for clay content however silt and sand fractions may have an influence on soil properties that affect strength characteristics and pitch rolling requirements. The influence of organic matter and grass roots on strength characteristics was also not determined. Future work is therefore required to expand soil characterisation for a wider range of soil types and physical characteristics.

Minimum moisture for cricket pitches was not established. The decline in strength between 8% and 15% moisture contents were not investigated and the results indicated that at some point the level of soil cohesion must rapidly decline. A rapid reduction in soil strength would result in pitch surface deterioration and a reduction in pace and ball rebound consistency.

The relationship between load and soil compaction developed a concept of increasing load requirement for compaction as dry bulk density increases and moisture declines. This technique could be developed as a way of using triaxial equipment to predict compaction under a load or to predict a maximum tolerance load before compaction occurs in agricultural soils.

3. Optimum moisture for a number of roller weights was determined; this was extended to cover a wider range of rollers however certain assumptions had to be made where data was not complete. Future work is necessary to develop optimum moistures for a greater range of roller weights.

Shrink/swell characteristics are crucial in the eventual dry bulk density of a cricket pitch for match play and need further study to predict increases in density from reductions in moisture content.

4. Field experiments examined soil moisture extensively over two years for spring and summer rolling on two cricket soils. The results apply directly to these soils and the climatic conditions encountered in these two years. Assumptions have therefore been made as to the validity of results across all soils and all climatic conditions and guideline recommendations made accordingly. Although the guidelines tend towards caution and adhere to basic principles future work should be undertaken to ensure that results achieved by groundsmen are those assumed from the results of this research. Recommendations for future appraisal have been made in Section 8.5.5.

Field experiments used one roller with two mass options (ballasted and un-ballasted). Future work is required to investigate the benefits of larger rollers and to match the higher rollers masses used in the rolling simulator (1250 kg m^{-1}).

5. Grass rooting experiments provided a basic understanding of rooting into compacted cricket soils in controlled conditions. The rooting pots were 300 mm deep with the lower end partially sealed allowing minimal air contact however it may have influenced gaseous exchange in the upper 200 mm of soil and effected root growth. This study needs to be extended to a natural cricket pitch profile to assess the root growth in natural conditions where limitations to gaseous exchange could reduce root growth.

Cricket soil types have previously only been selected for their mechanical strength and drying properties however results indicated large differences between soil types for root growth and further work needs to be undertaken to ascertain which cricket soils are more likely to reduce root growth and whether this affects pitch strength characteristics and soil drying.

More work needs to be done to establish the relationship between grass root and leaf growth and moisture removal which could inform the process of even drying of the cricket pitch.

6. Rolling simulator experiments developed the technique for video capture of soil movement which impinged on the time available for a more extensive experimental programme. Time restrictions did not allow for development of initial results in particular the benefits and disbenefits of larger diameter rollers and the use of rollers diameters smaller than standard cricket rollers which could result in greater horizontal soil movement. A tendency to reduce horizontal movement from the faster speed was also observed although this was not statistically significant and could be investigated further in future work.

Cricket simulator experiments were undertaken with a towed roller which left soil particles forward of their initial position. A driven roller has been shown by other work to leave soil particles behind the initial position. Cricket rollers commonly have a driven roller drum together with a towed roller or individually. Future work is required to characterise the difference in soil dynamic behaviour between these roller types and also when driven in tandem.

9.4 Publications from this project

Publications (Appendix 13 and 14):

Shipton, P., James, I. & Vickers, A. (2006) *The Mechanical Behaviour of Cricket Soils During Preparation by Rolling.* The Engineering of Sport 6, Volume 1: Developments for Sports. E F Moritz & S Haake (Eds.), Springer, NY, USA. ISBN-10: 0-387-31773-2, p 229-234

Shipton, P. & James, I. (2008) *The Dynamic Compaction of Cricket Soils for Pitch Preparation.* The Engineering of Sport 7, Volume 1: M. Estivalet & P. Brisson (Eds.), Springer-Verlag France, Paris, ISBN-13: 978-287-09410-1, p 107-113

In Preparation:

The relationship between total porosity, rooting and soil biology in cricket pitch soils. Shipton, P.M.R., Bartlett M. D. and James, I.T. ITRC 2009

Grass root penetration and distribution in compacted cricket loam soils

Soil movement under a roller – an analysis using video / Matlab mapping of soil movement under different soil and roller parameters

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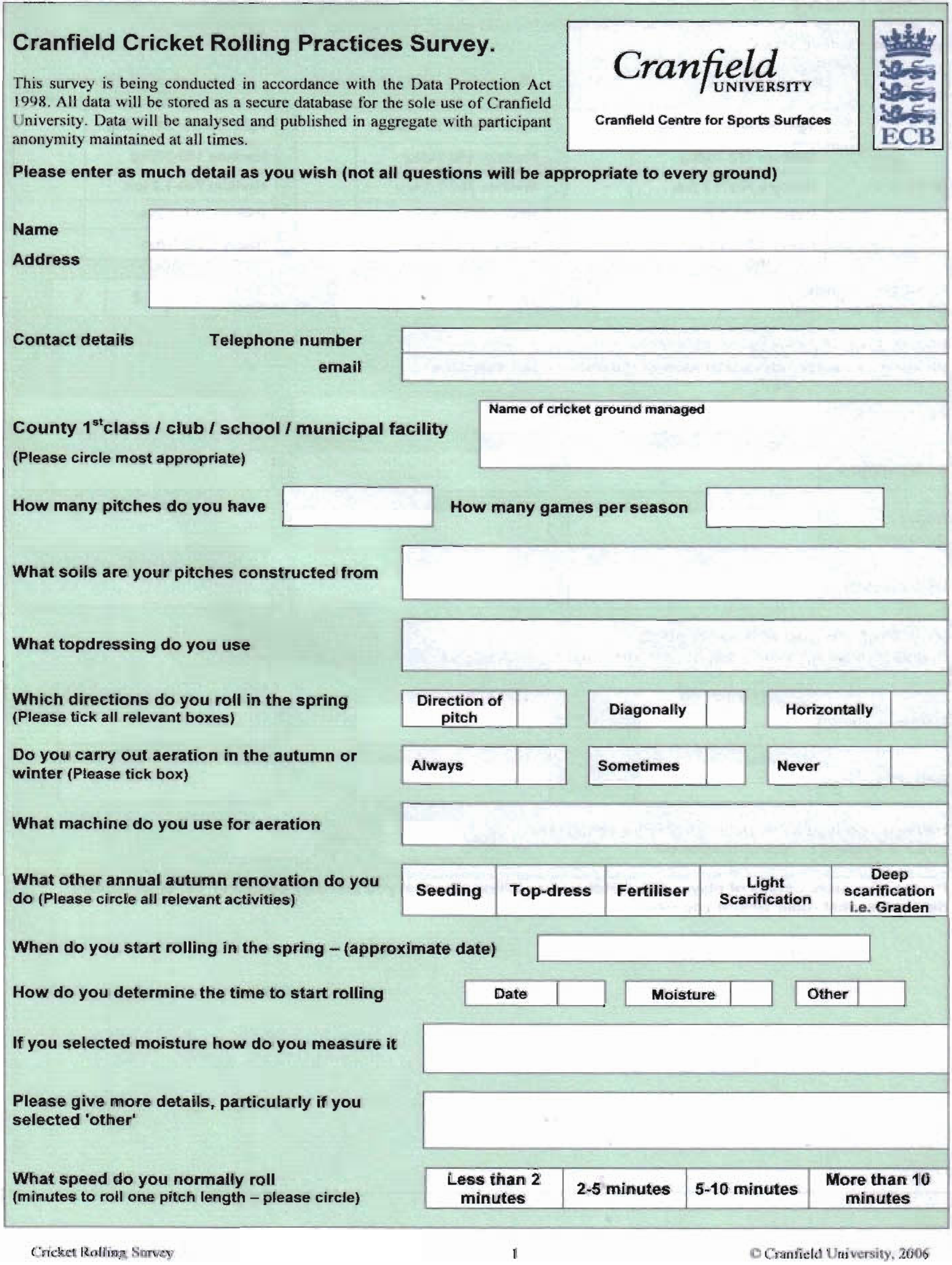
Appendix 1 Performance Quality Standards (reproduced from IOG 2004)

Performance standard	**Quality Standard**		
Structural quality	**High**	**Standard**	**Basic**
Herbage:			
Length of herbage: to be within	2 to 3 mm	4 to 5 mm	6 to 7 mm
Total ground cover			
Maximum	40%	60%	70%
Minimum	25%	30%	50%
Weeds - large leaved	nil	nil	nil
Weeds - small leaved	nil	nil	max 5%
Moss	nil	nil	nil
Algae and Lichen	nil	nil	nil
Pests and Diseases:			
Diseases	nil	nil	nil
Earthworms	nil	nil	max 2%
Pests and Diseases	nil	nil	nil
Profile:			
root depth: minimum	125 mm	100 mm	75 mm
Thatch depth	nil	nil	nil
Soil strength: minimum	70 kg	60 kg	45
Evenness: max variation			
2 m straight edge	4 mm	8 mm	10 mm
0.5 m straight edge	3 mm	4 mm	6 mm
Presentational quality			
Appearance	100% uniform	90% uniform	70% uniform
Surface debris	nil	nil	nil
Sward colour	100% uniform	90% uniform	70% uniform
Width of pitch markings	12-18 mm	12-18 mm	12-18 mm
Visibility of pitch markings	From 25 m	22 m	20 m
Playing Quality			
Vertical ball rebound	16-21%	12-15%	8-11% slow
ECB PQS - guidelines	22-24% very fast	17-21% fast	12-16% easy pace
Traction: minimum	25 Nm	20 Nm	20 Nm
Disintegration of the surface	nil	nil	Max 2%
Evenness (disturbance) 0.5 m straight edge	nil	max 2 mm	
Spin: minimum	400 mm	300-450 mm	
Hardness: minimum (2.5 kg)	400 gravities	300 gravities	200 gravities

Appendix 2 Cricket rolling survey questionnaire



Cranfield Cricket Rolling Practices Survey.

Cranfield UNIVERSITY
Cranfield Centre for Sports Surfaces

ECB

This survey is being conducted in accordance with the Data Protection Act 1998. All data will be stored as a secure database for the sole use of Cranfield University. Data will be analysed and published in aggregate with participant anonymity maintained at all times.

Please enter as much detail as you wish (not all questions will be appropriate to every ground)

Name

Address

Contact details **Telephone number**

email

County 1st class / club / school / municipal facility
(Please circle most appropriate)

Name of cricket ground managed

How many pitches do you have **How many games per season**

What soils are your pitches constructed from

What topdressing do you use

Which directions do you roll in the spring (Please tick all relevant boxes)
Direction of pitch ☐ Diagonally ☐ Horizontally ☐

Do you carry out aeration in the autumn or winter (Please tick box)
Always ☐ Sometimes ☐ Never ☐

What machine do you use for aeration

What other annual autumn renovation do you do (Please circle all relevant activities)

Seeding	Top-dress	Fertiliser	Light Scarification	Deep scarification i.e. Graden

When do you start rolling in the spring – (approximate date)

How do you determine the time to start rolling
Date ☐ Moisture ☐ Other ☐

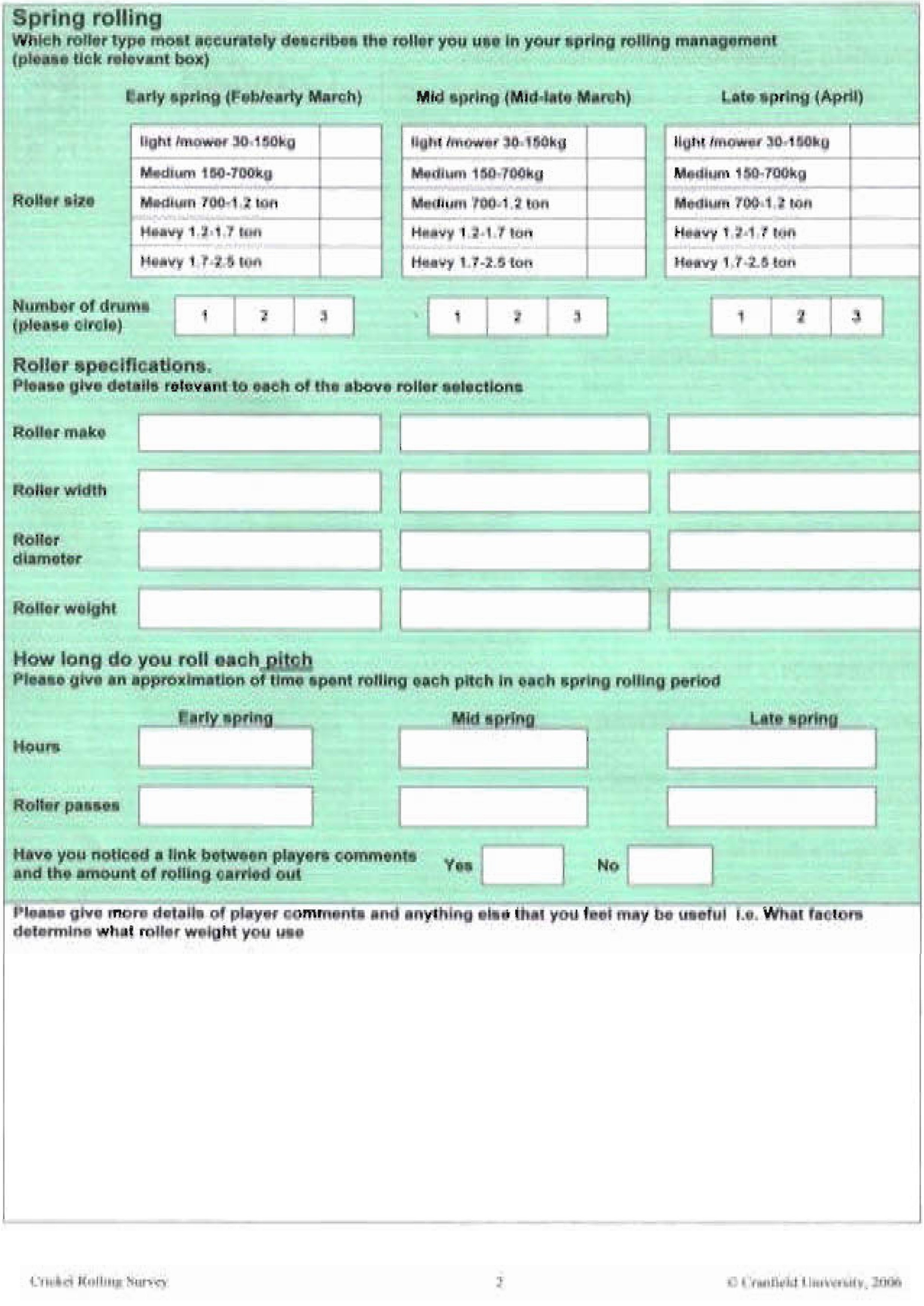
If you selected moisture how do you measure it

Please give more details, particularly if you selected 'other'

What speed do you normally roll
(minutes to roll one pitch length – please circle)

Less than 2 minutes	2-5 minutes	5-10 minutes	More than 10 minutes

Cricket Rolling Survey 1 © Cranfield University, 2006



Spring rolling

Which roller type most accurately describes the roller you use in your spring rolling management (please tick relevant box)

	Early spring (Feb/early March)		Mid spring (Mid-late March)		Late spring (April)	
Roller size	light /mower 30-150kg	☐	light /mower 30-150kg	☐	light /mower 30-150kg	☐
	Medium 150-700kg	☐	Medium 150-700kg	☐	Medium 150-700kg	☐
	Medium 700-1.2 ton	☐	Medium 700-1.2 ton	☐	Medium 700-1.2 ton	☐
	Heavy 1.2-1.7 ton	☐	Heavy 1.2-1.7 ton	☐	Heavy 1.2-1.7 ton	☐
	Heavy 1.7-2.5 ton	☐	Heavy 1.7-2.5 ton	☐	Heavy 1.7-2.5 ton	☐
Number of drums (please circle)	1 2 3		1 2 3		1 2 3	

Roller specifications.
Please give details relevant to each of the above roller selections

Roller make			
Roller width			
Roller diameter			
Roller weight			

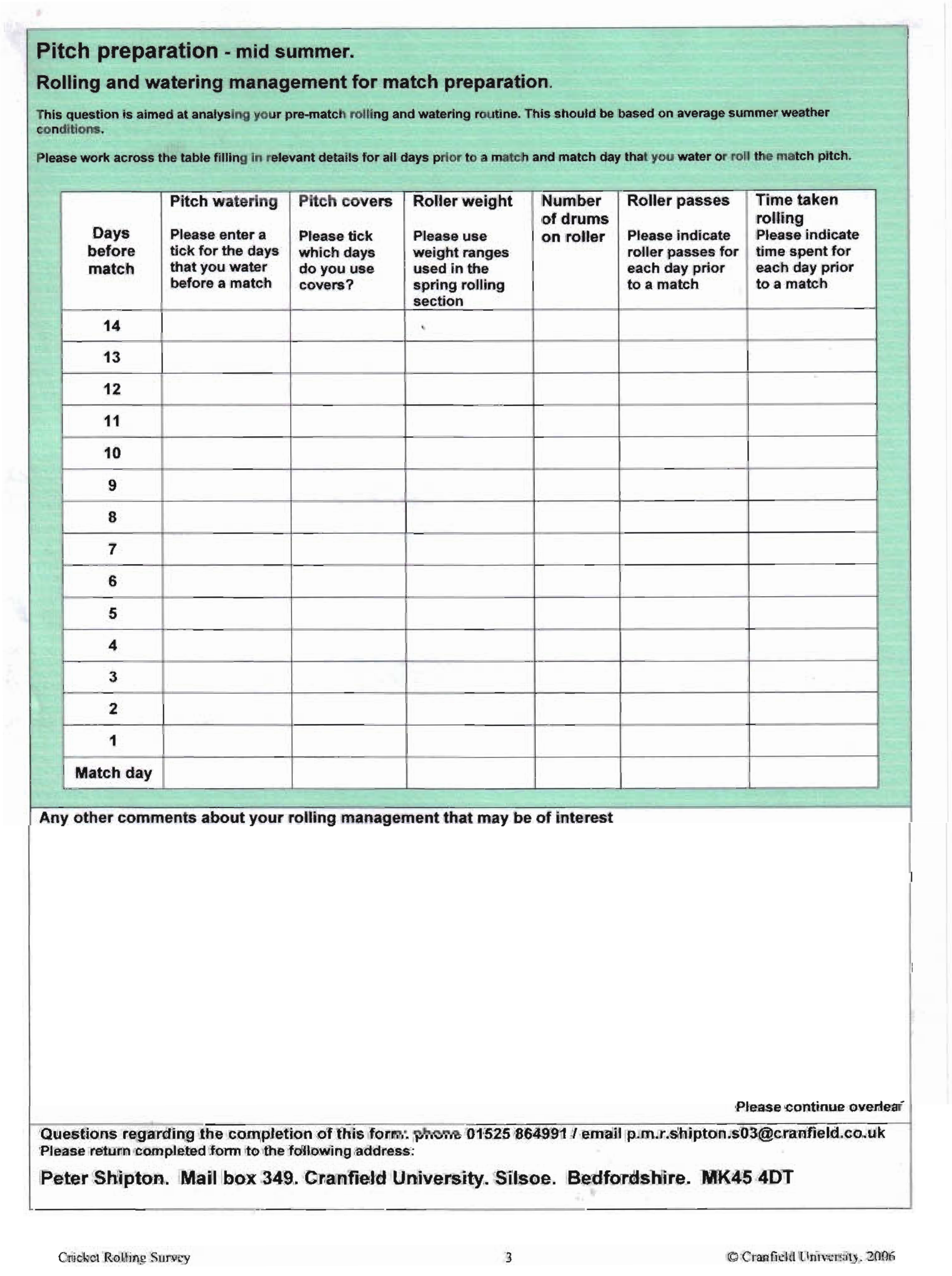
How long do you roll each pitch
Please give an approximation of time spent rolling each pitch in each spring rolling period

	Early spring	Mid spring	Late spring
Hours			
Roller passes			

Have you noticed a link between players comments and the amount of rolling carried out Yes ☐ No ☐

Please give more details of player comments and anything else that you feel may be useful i.e. What factors determine what roller weight you use

Cricket Rolling Survey 2 © Cranfield University, 2006



Pitch preparation - mid summer.

Rolling and watering management for match preparation.

This question is aimed at analysing your pre-match rolling and watering routine. This should be based on average summer weather conditions.

Please work across the table filling in relevant details for all days prior to a match and match day that you water or roll the match pitch.

Days before match	Pitch watering Please enter a tick for the days that you water before a match	Pitch covers Please tick which days do you use covers?	Roller weight Please use weight ranges used in the spring rolling section	Number of drums on roller	Roller passes Please indicate roller passes for each day prior to a match	Time taken rolling Please indicate time spent for each day prior to a match
14						
13						
12						
11						
10						
9						
8						
7						
6						
5						
4						
3						
2						
1						
Match day						

Any other comments about your rolling management that may be of interest

Please continue overleaf

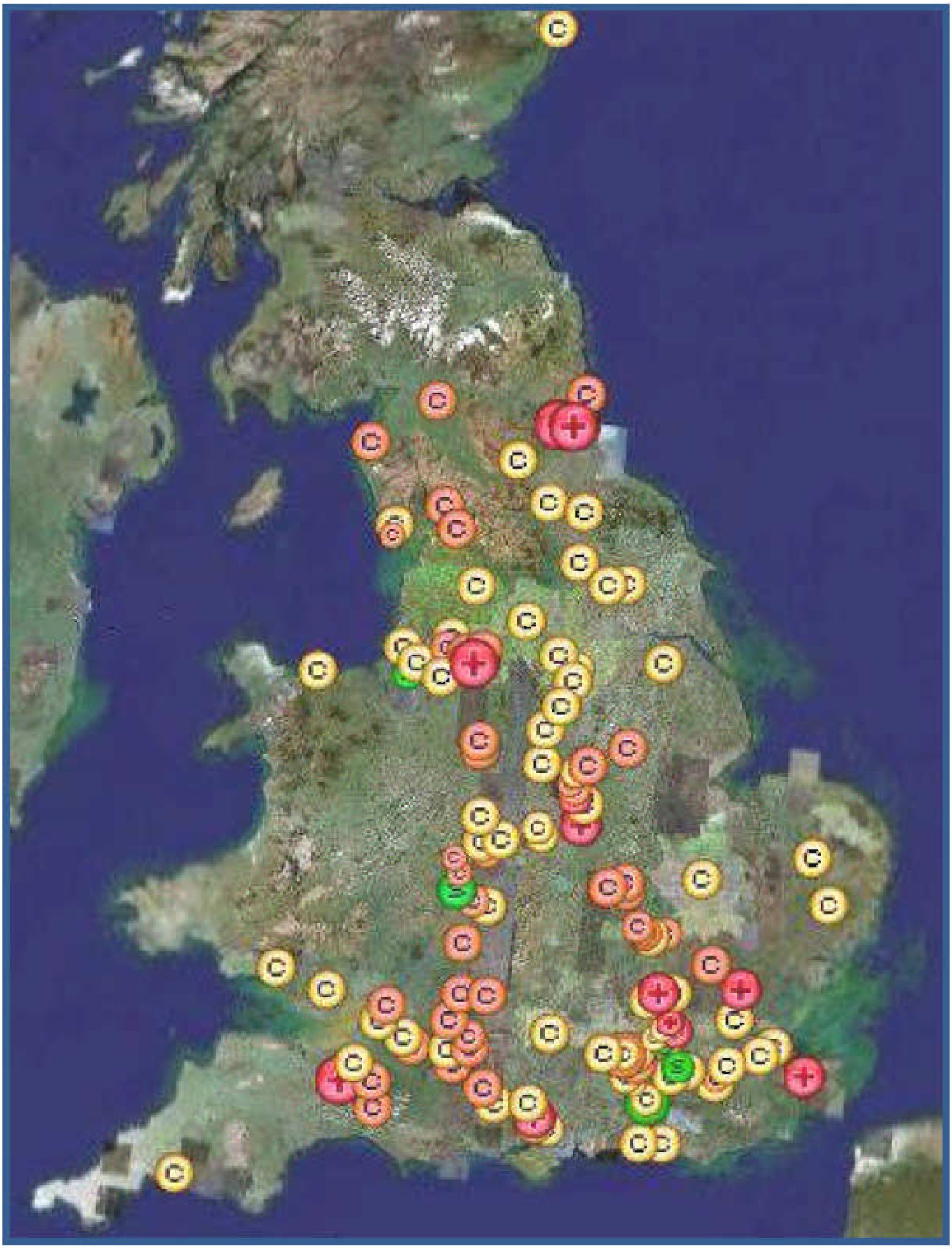
Questions regarding the completion of this form: phone 01525 864991 / email p.m.r.shipton.s03@cranfield.co.uk
Please return completed form to the following address:

Peter Shipton. Mail box 349. Cranfield University. Silsoe. Bedfordshire. MK45 4DT

Cricket Rolling Survey 3 © Cranfield University, 2006

Appendix 3 Rolling survey respondents

(C) yellow = club internet return, (C) pink = club postal return, (+) red = first class, (S) green = school



Appendix 4 Survey data not presented in main text

Aeration machine used

Aeration_machine		Frequency	Percent	Valid Percent	Cumulative
Valid	no aeration	7	5.4	5.4	5.4
	Groundsman	31	23.8	24.0	29.5
	other	26	20.0	20.2	49.6
	Vertidrain	5	3.8	3.9	53.5
	Toro procore	4	3.1	3.1	56.6
	Sisis	20	15.4	15.5	72.1
	dont know	30	23.1	23.3	95.3
	Sarrel roller	6	4.6	4.7	100.0
	Total	129	99.2	100.0	
Missing	System	1	.8		
Total		130	100.0		

Mean roller specifications – all facilities

Roller specs summary	Roller width	Roller diameter	Roller mass
Early spring			
Mean	0.90	0.43	561
Range	1.75	1.45	3470
Minimum	0.25	0.05	30
Maximum	2	1.5	3500
Mid spring			
Mean	1.04	0.61	1376
Range	1.80	1.35	3499
Minimum	0.60	0.15	2
Maximum	2.40	1.50	3500
Late spring			
Mean	1.13	0.71	1709
Range	1.80	1.20	3350
Minimum	0.60	0.30	150
Maximum	2.40	1.50	3500

Roller drums

Roller drums Early		Frequency	Percent	Valid Percent	Cumulative
Valid	1 drum	62	47.7	58.5	58.5
	2 drums	37	28.5	34.9	93.4
	3 drums	7	5.4	6.6	100.0
	Total	106	81.5	100.0	
Missing	System	24	18.5		
Total		130	100.0		

Roller drums Mid		Frequency	Percent	Valid Percent	Cumulative
Valid	1 drum	25	19.2	20.5	20.5
	2 drums	81	62.3	66.4	86.9
	3 drums	16	12.3	13.1	100.0
	Total	122	93.8	100.0	
Missing	System	8	6.2		
Total		130	100.0		

Roller drum Late spring		Frequency	Percent	Valid Percent	Cumulative
Valid	1 drum	4	3.1	3.5	3.5
	2 drums	87	66.9	77.0	80.5
	3 drums	22	16.9	19.5	100.0
	Total	113	86.9	100.0	
Missing	System	17	13.1		
Total		130	100.0		

Roller make

Roller make early		Frequency	Percent	Valid Percent	Cumulative
Valid	dont know	13	10.0	14.4	14.4
	Autoroller/T H	3	2.3	3.3	17.8
	Bomag	2	1.5	2.2	20.0
	Stothert & Pitt	2	1.5	2.2	22.2
	other	69	53.1	76.7	98.9
	Aveling barford	1	.8	1.1	100.0
	Total	90	69.2	100.0	
Missing	System	40	30.8		
Total		130	100.0		

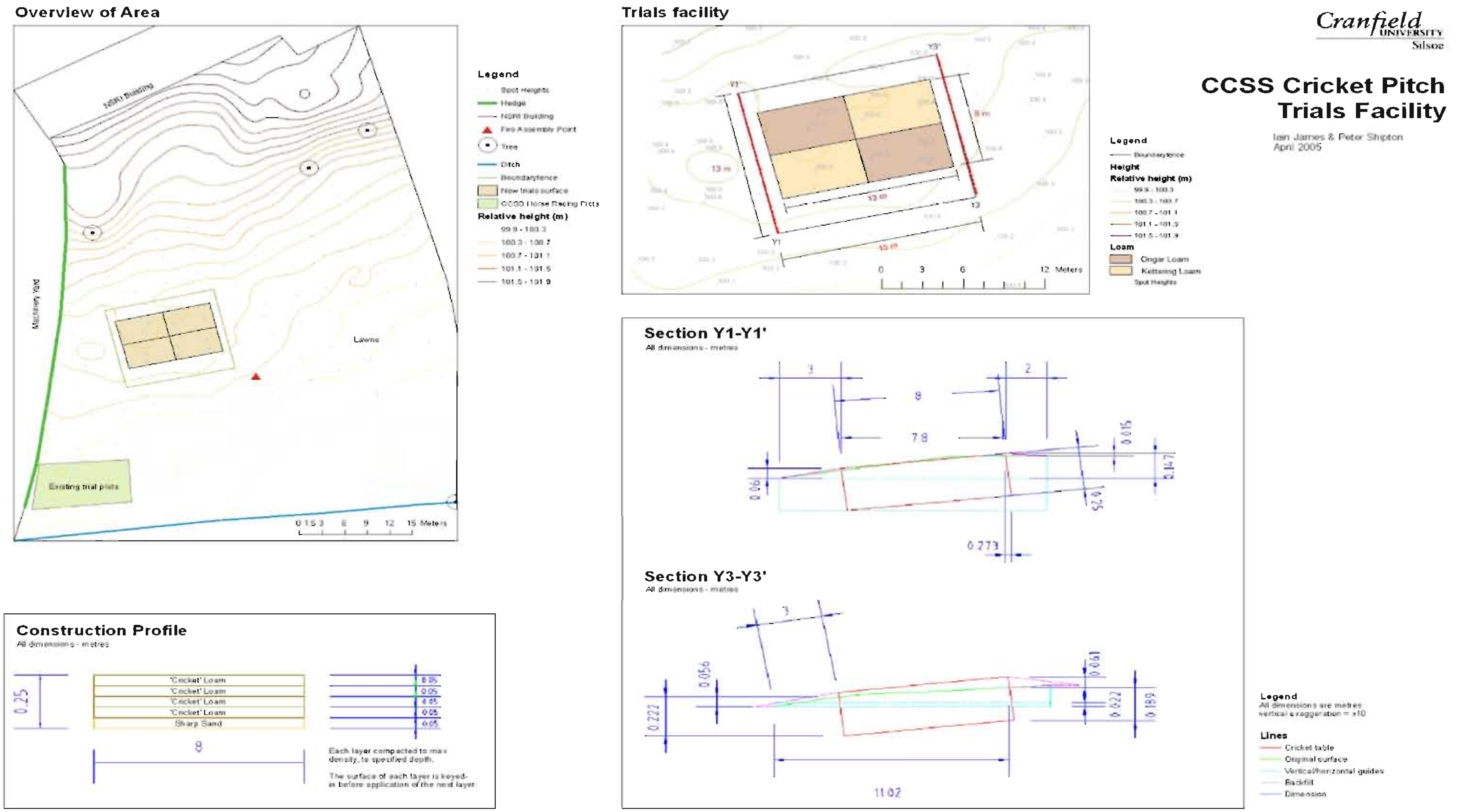
Roller make mid spring		Frequency	Percent	Valid Percent	Cumulative
Valid	don't know	9	6.9	8.8	8.8
	Autoroller/T H	27	20.8	26.5	35.3
	Sisis	3	2.3	2.9	38.2
	Bomag	10	7.7	9.8	48.0
	Stothert & Pitt	6	4.6	5.9	53.9
	other	43	33.1	42.2	96.1
	Aveling barford	4	3.1	3.9	100.0
	Total	102	78.5	100.0	
Missing	System	28	21.5		
Total		130	100.0		

Roller make late spring		Frequency	Percent	Valid Percent	Cumulative
Valid	don't know	14	10.8	13.9	13.9
	Autoroller/T H	28	21.5	27.7	41.6
	Bomag	13	10.0	12.9	54.5
	Stothert & Pitt	11	8.5	10.9	65.3
	other	27	20.8	26.7	92.1
	Aveling Barford	8	6.2	7.9	100.0
	Total	101	77.7	100.0	
Missing	System	29	22.3		
Total		130	100.0		

Appendix 5 Pitch monitoring data

	09/03/2005			01/07/2005			11/10/2005				22/02/2006		
Facility and sample	Moisture		density ρ_d	Moisture		density ρ_d		Moisture	density ρ_d	Winter	Moisture		density ρ_d
Leicester CC	Grav %	Volume %	g cm^{-3}	Grav %	Volume %	g cm^{-3}	Grav %	Volume %	g cm^{-3}	aeration	Grav %	Volume %	g cm^{-3}
Pitch 11 0-30 mm	39.85	54.12	1.36	17.36	28.83	1.66	23.46	40.27	1.72	Yes	35.60	45.90	1.29
Pitch 11 30-60 mm	27.91	39.28	1.41	15.74	25.38	1.61	20.99	31.46	1.50	Yes	31.65	45.38	1.43
Pitch 11 60-90 mm	*	*	*	20.71	39.87	1.93	21.92	33.40	1.52	Yes	28.24	36.48	1.29
Pitch 11 100-140 mm	*	*	*	21.37	31.65	1.48	21.81	34.10	1.56	No	27.56	43.83	1.59
Pitch 11 140-190 mm	*	*	*	20.22	37.16	1.84	19.53	38.01	1.95	No	*	*	
Pitch 4 0-30 mm	45.10	55.55	1.23	23.43	36.55	1.56	30.09	48.33	1.61	Yes	34.03	49.76	1.46
Pitch 4 30-60 mm	39.16	49.02	1.25	22.37	34.46	1.54	28.81	43.34	1.50	Yes	28.72	40.31	1.40
Pitch 4 60-90 mm	*	*	*	21.74	34.96	1.61	26.60	48.17	1.81	Yes	22.03	38.29	1.74
Pitch 4 90-120 mm	*	*	*	17.11	34.65	1.62	23.31	40.89	1.75	No	26.32	37.86	1.44
nets, pitch 2, 0-30 mm	36.86	47.21	1.28	16.36	24.49	1.50	29.44	43.34	1.47	Yes	38.95	51.71	1.33
nets, pitch 2, 30-60 mm	27.36	40.88	1.49	14.21	25.46	1.79	21.33	35.01	1.64	Yes	25.04	40.62	1.62
nets, pitch 2, 60-90 mm	18.86	31.70	1.68	11.47	24.18	1.72	18.29	29.20	1.60	No	18.55	31.71	1.71
nets, pitch 2, 90-120 mm	16.43	28.27	1.72	*	*	*	18.29	33.04	1.81	No	19.20	32.83	1.71
Shenley CC													
0 - 30 mm	32.10	49.35	1.54	38.14	53.59	1.40	21.22	30.93	1.46	No	42.43	51.47	1.41
30 - 60 mm	18.13	35.76	1.97	19.03	35.95	1.89	19.83	38.06	1.92	No	19.05	35.59	1.87
60 - 90 mm	18.50	36.43	1.97	15.78	31.30	1.92	17.18	28.61	1.67	No	18.35	31.35	1.71
90 -120 mm	23.90	44.15	1.85	14.94	33.81	1.91	16.51	30.32	1.84	No	20.11	31.14	1.55
120-155 mm	26.31	*	*	18.51	35.31	1.91	20.69	31.46	1.52	No	19.51	31.42	1.61
Cranfield CC													
Pitch 1 0-30 mm	32.43	33.66	1.04	18.22	21.39	1.17	30.99	38.30	1.24	Yes	50.75	54.50	1.07
Pitch 1 30-60 mm	24.93	30.82	1.24	15.90	21.80	1.37	22.78	38.04	1.67	Yes	31.22	45.28	1.45
Pitch 1 60-90 mm	13.52	*	*	12.61	*	*	17.15	28.60	1.67	Yes	22.70	33.25	1.46
Pitch 1 90-120 mm	*	*	*	*	*	*	15.60	24.72	1.58	No	19.11	35.64	1.87
Pitch 2 0-30 mm	28.95	30.32	1.05	16.63	19.22	1.16	33.84	42.86	1.27	Yes	52.65	58.59	1.11
Pitch 2 30-60 mm	28.63	33.43	1.17	20.58	26.38	1.28	30.09	46.33	1.54	Yes	35.10	48.10	1.37
Pitch 2 60-90 mm	32.49	*	*	23.36	31.87	1.36	32.23	50.31	1.56	Yes	36.71	47.28	1.29
Pitch 2 90-120 mm	*	*	*	27.48	37.33	1.36	33.09	50.03	1.51	No	36.05	38.60	1.07

Appendix 6 Cricket Pitch Trials Facility

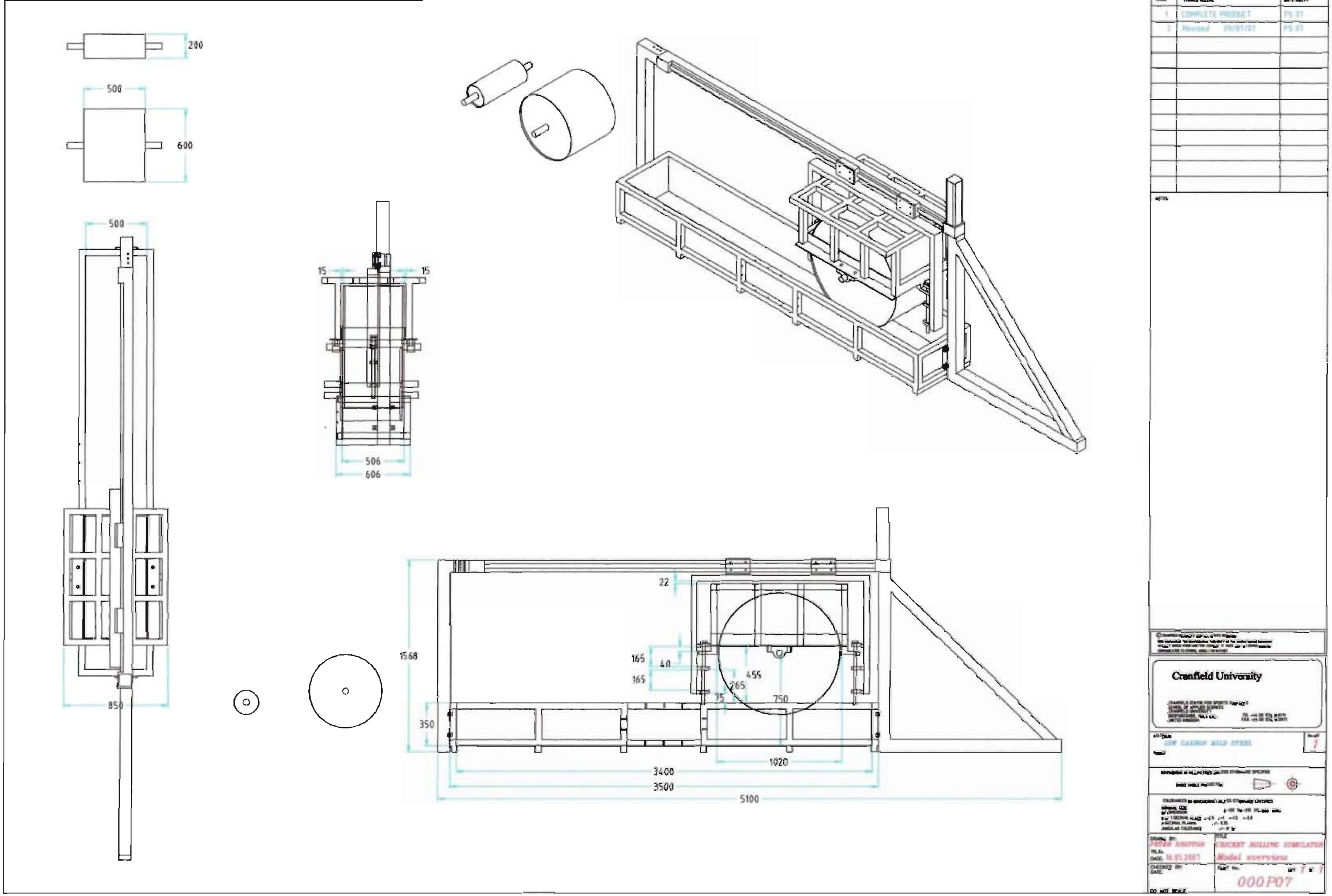


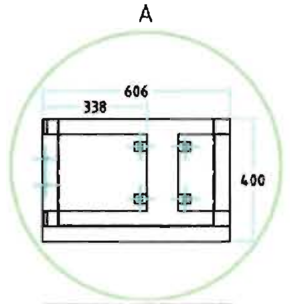
Appendix 7 Experimental parameters for cricket plot experiments

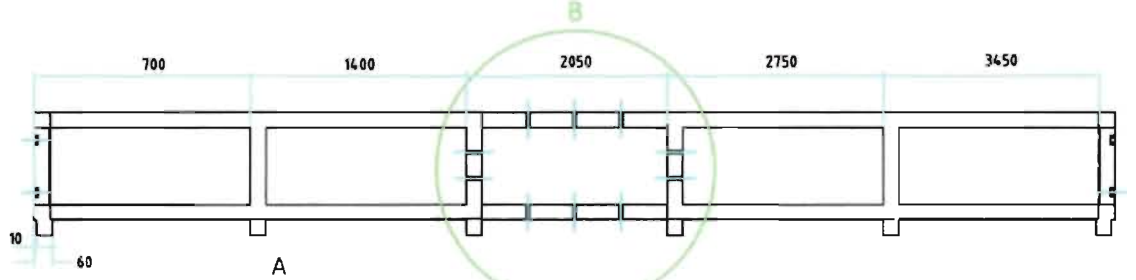
Exp	Date	Parameters assessed	Treatment	Roller sessions	Total roller passes	Roller mass	Speed	Moisture	Measurements	Measurement frequency each session
					no.	kg m^{-1}	km h^{-1}	θ_m%	taken	passes
1	spring 2006	Spring rolling; Multiple sessions	1	6	60	725	0.7	> 23%	DM, C, S, PR	0, 2, 4, 6, 10
			-	control	0	0	0	various	DM, C, S, PR	0 – each session
2	spring 2006	Spring rolling; Single session	1	1	28	920	0.7	> 23%	DM, C, S, PR	0, 2, 4, 6, 11
			-	control	0	0	0	various	DM, C, S, PR	0 – each session
3	summer 2006	920 kg m^{-1}	1	2	30	920	0.7	20% / 18%	DM, C, S, PR	0, 5, 10, 15
			-	control	0	0	0	various	DM, C, S, PR	0 – each session
4	spring 2007	2 roller speeds 0.9 km h^{-1}	1	3	18	920	0.9	27% - 17%	DM, C, PR	0, 2, 4, 6
		0.45 km m^{-1}	2	3	18	920	0.45	27% - 17%	DM, C, PR	0, 2, 4, 7
			3	control	0	0	0	various	DM, C, PR	0 - each session
5	summer 2007	Daily rolling	1	13	28	920	0.35	saturated to 15%	DM, C, BR, Cr	after rolling daily
		Reduced rolling	2	5	30	920	0.35	saturated to 15%	DM, C, BR, Cr	before and after rolling every 3 days
			3	control	0	0	0	saturated to 15%	DM, C, BR, Cr	end of final day only

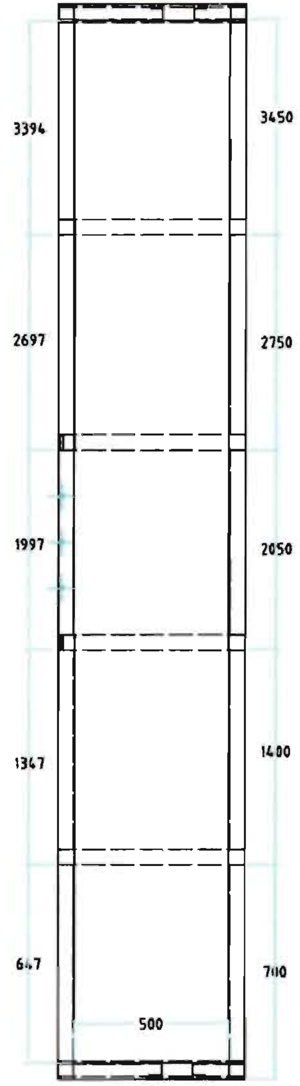
Measurement key:
Dry bulk density and moisture core (DM), Clegg hammer 0.5 kg (C), shear vane (S), penetration resistance (PR), 3 m ball rebound (BR), cracking (Cr)

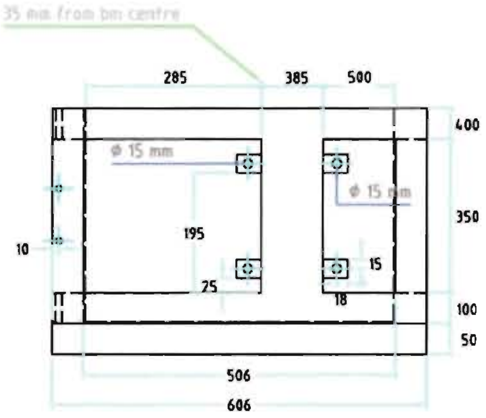
Appendix 8 Cricket rolling simulator design drawings

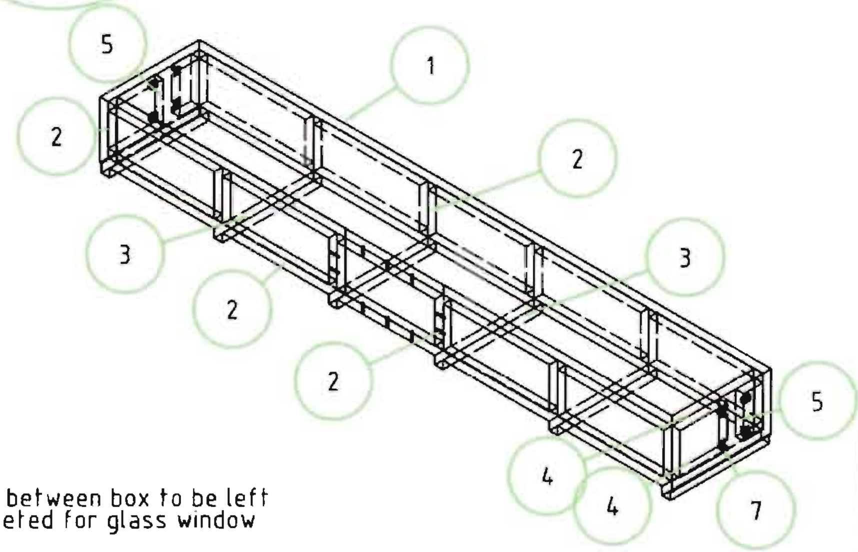












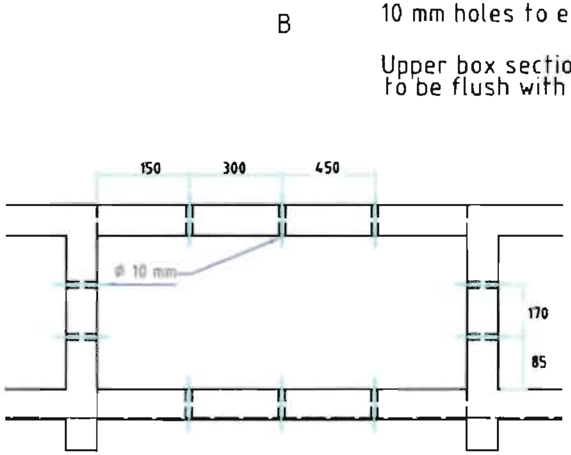
All joints weld arround unless specified otherwise.
Fillet weld min leg=7mm

Bin lined with steel sheet leaving window panel as detailed (B)

Panel between box to be left unsheeted for glass window

10 mm holes to extreme edge of box

Upper box section of window opening to be sheeted to be flush with adjoining sheeted bin lining



Cutting List

[illegible]	[illegible]	[illegible]	[illegible]
1	Box 50x50x3	3500	4
2	Box 50x50x3	250	12
3	Box 50x50x3	410	4
4	Box 50x50x3	510	4
5	Box 100x50x3	250	2
6	3 mm steel plate	approximately 4.2 m2	
7	15 mm plate	30x40	8

PART No. 001P07

1	complete soil bin	PS 07
2	amended PS	[illegible]

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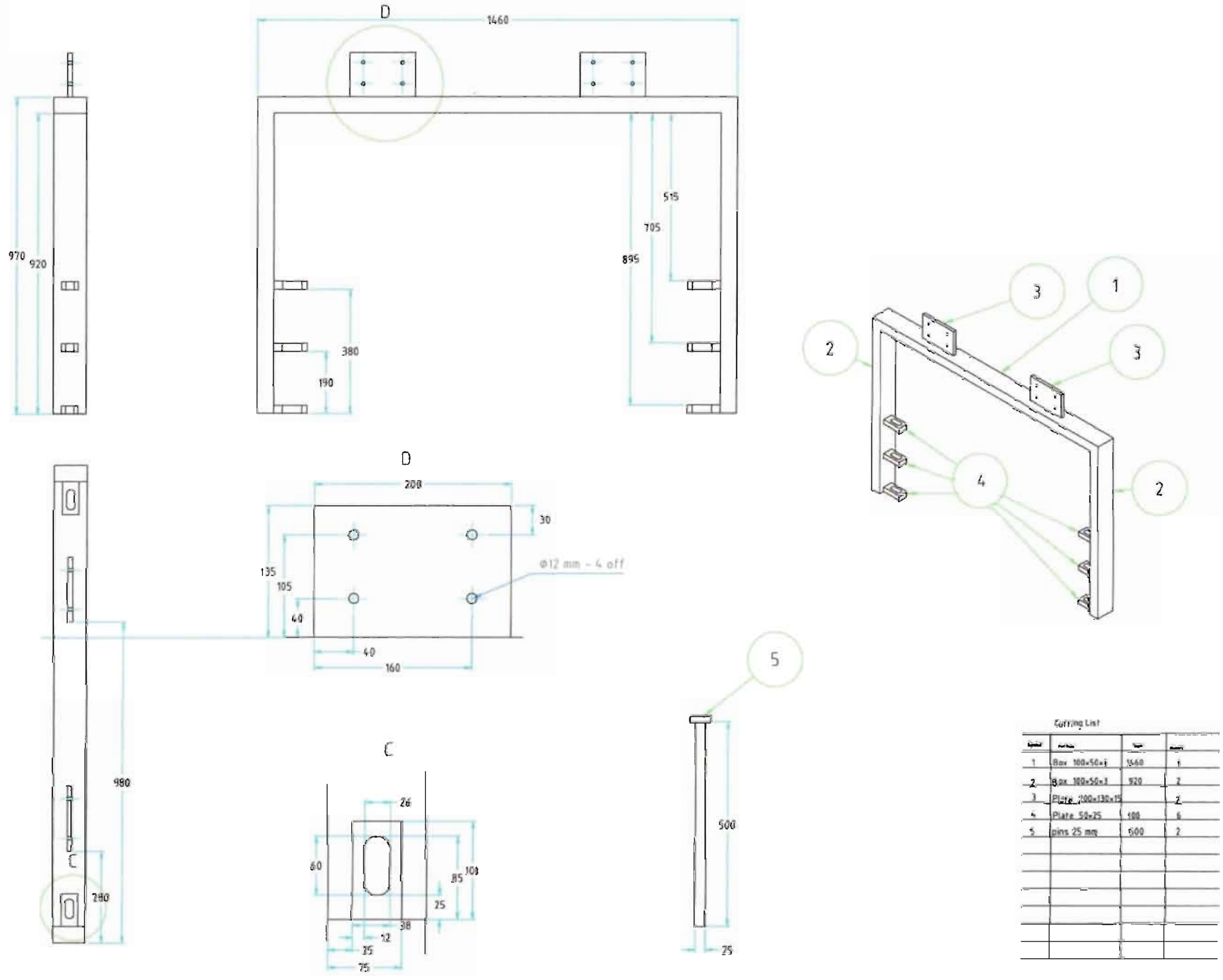
LOW CARBON MILD STEEL

Soil Bin

PART No. 001P07

1 of 1



Cutting List

[illegible]	[illegible]	[illegible]	[illegible]
1	Box 100×50×3	1460	1
2	Box 100×50×3	920	2
3	Plate 200×130×15		2
4	Plate 50×25	100	6
5	pins 25 mm	500	2

PART No 003P07

[illegible]	CHANGE [illegible]	DATE [illegible]
1	Top Drive Frame	PS 07
2	Revised 27/03/07	PS 07

All joints weld arround unless specified otherwise.
Fillet weld min leg=7mm

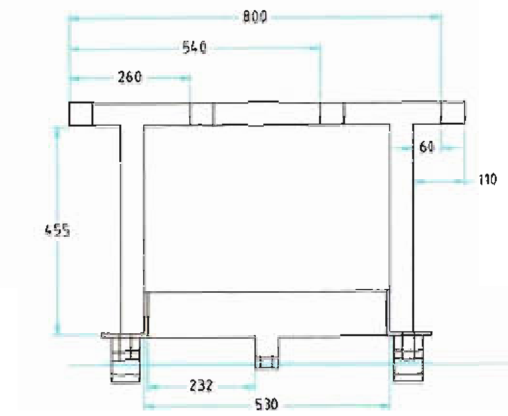
MATERIAL LOW CARBON MILD STEEL
SHEET 1

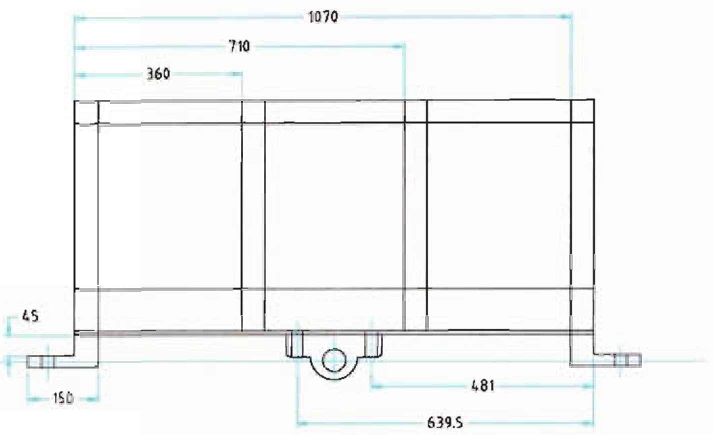
DRAWN BY PETER SHIPTON
DATE 16.03.2007

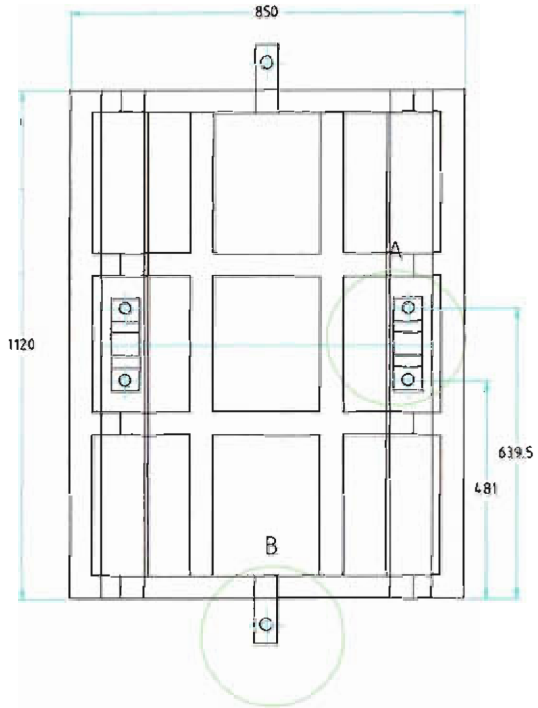
TITLE CRICKET BOWLING SIMULATOR
Top drive Frame

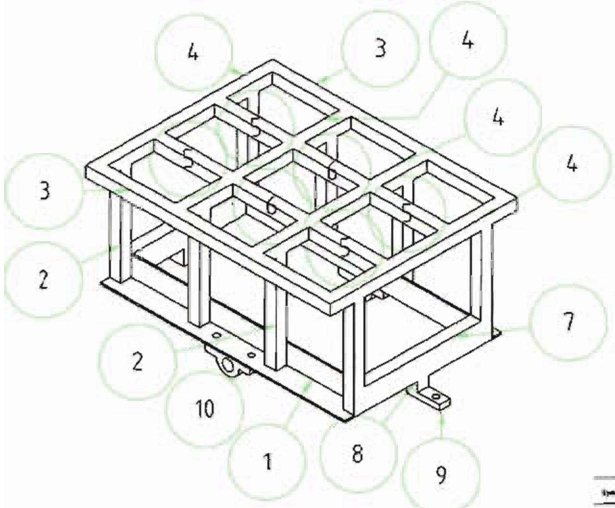
PART No 003P07
SHT 1 of 1

DO NOT SCALE

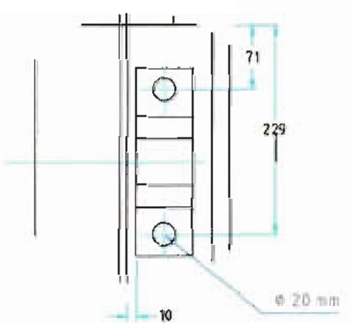




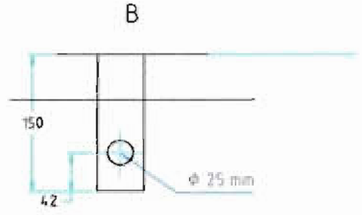




A



B



Cutting List

Symbol	Material	Length	Quantity
1	Angle 100x100x5	1120	2
2	Box 50x50x3	455	8
3	Box 50x50x3	1120	2
4	Box 50x50x3	750	4
5	Box 50x50x3	310	4
6	Box 50x50x3	300	2
7	Box 100x50x3	514	2
8	steel 50x50	45	2
9	steel 25x50	150	2
10	50 mm Plummer block		2

PART No. 002P07

ISSUE	CHANGE RECORD	DATE - AUTHOR
1	Roller frame	PS 07
2	Revised 24/07/07	PS

NOTES:

All joints weld arround
unless specified
otherwise.
Fillet weld min leg=7mm

Draw bar detailed (A)

CRANFIELD CENTRE FOR SPORTS SURFACES
SCHOOL OF APPLIED SCIENCES
CRANFIELD UNIVERSITY
BEDFORDSHIRE, MK43 0AL
UNITED KINGDOM
TEL [illegible]
FAX [illegible]

MATERIAL
LOW CARBON MILD STEEL
FINISH

SHEET 1

DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED

THIRD ANGLE PROJECTION

TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION
0 or 1 DECIMAL PLACE
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'

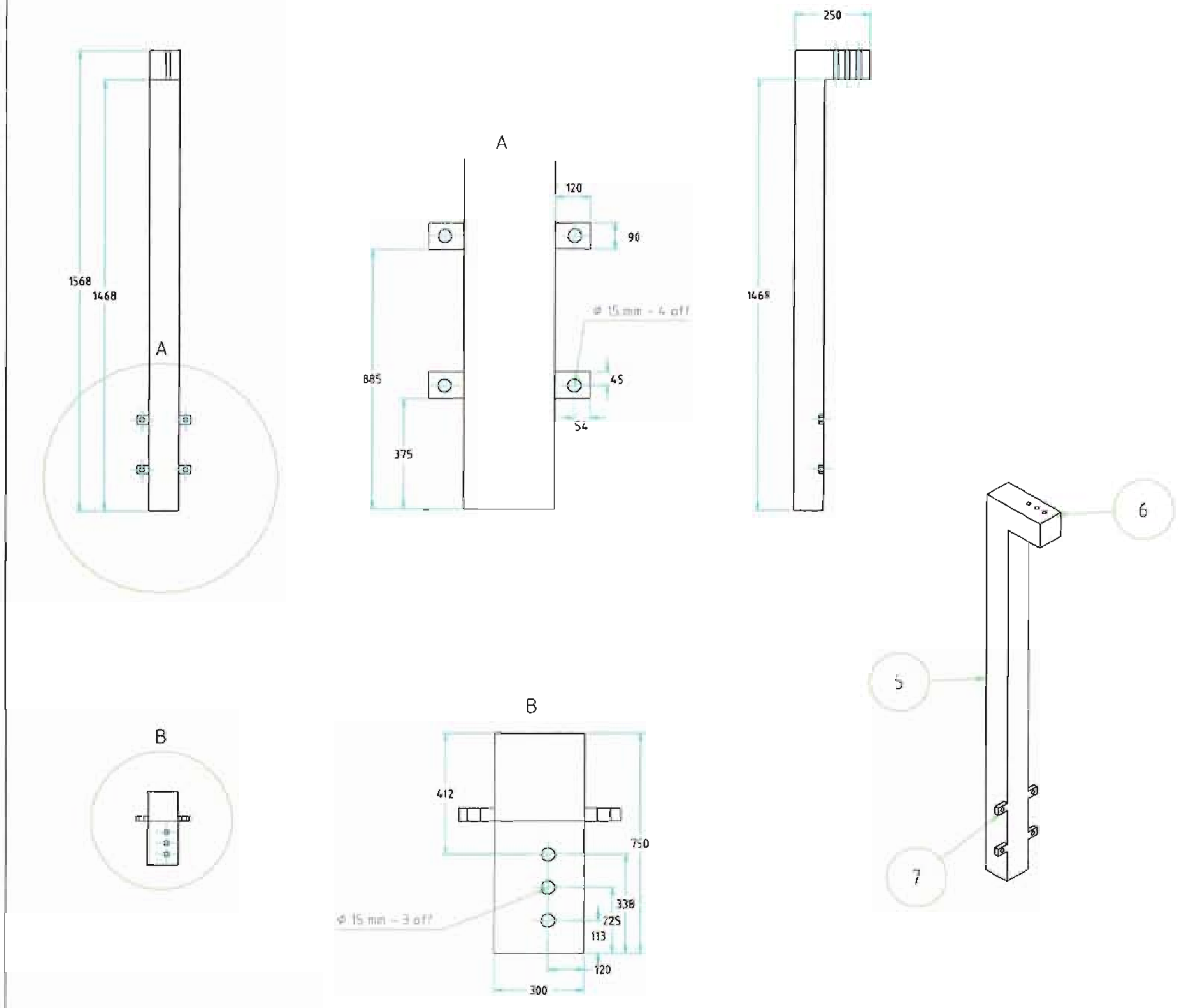
DRAWN BY: [illegible]
TEL.Ex.
DATE: 16.05.2007

TITLE: CRICKET ROLLING SIMULATOR
Roller frame

CHECKED BY:
DATE:

PART No. 002P07
SHT 1 of 1

DO NOT SCALE



All joints weld arround unless specified otherwise.
Fillet weld min leg=7mm

Fixing plate holes 20 mm to align with similar on soil bin

Cutting List

End	Support 2		
5	Box 100x100x3	1470	1
6	Box 100x100x3	250	1
7	Plate 30x30x15		4

PART No 004P07 & 005P07

	CHANGE RECORD	DATE/AUTHOR
1	End Support 1/Rev	PS 07
2	Revised 29/07/07	PS 07

NOTES

CRANFIELD CENTRE FOR SPORTS IMPACTS
SCHOOL OF APPLIED SCIENCES
CRANFIELD UNIVERSITY
BEDFORDSHIRE, MK43 0AL
UNITED KINGDOM

MATERIAL: LOW CARBON MILD STEEL

FINISH:

DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED

THIRD ANGLE PROJECTION

TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED

DRAWN BY: PETER SAWYER

DATE: 16.05.2007

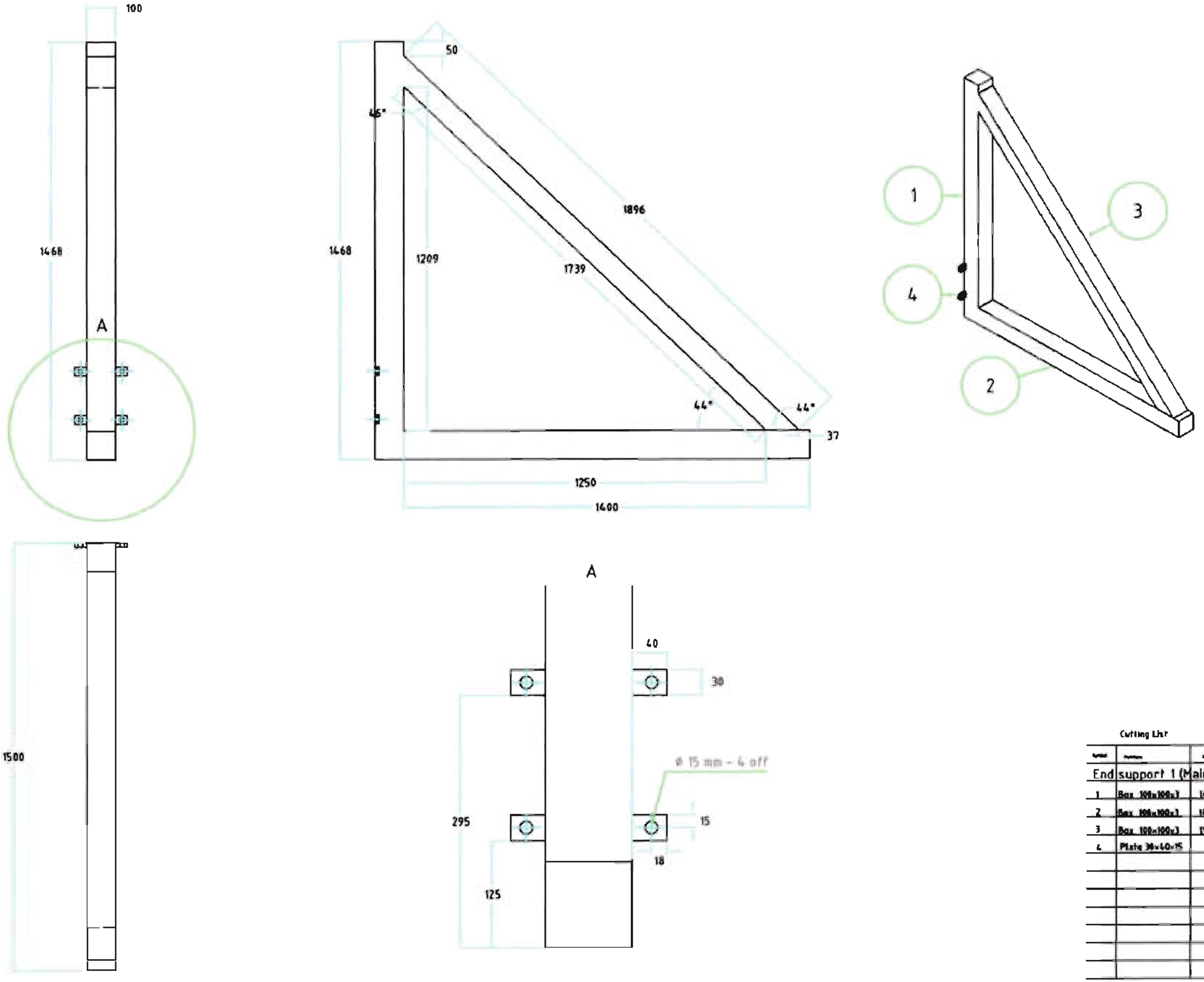
TITLE: CRICKET ROLLING SIMULATION Support Posts

CHECKED BY:
DATE:

PART NO: 004P07 & 005P07

SHEET 1 of 1

DO NOT SCALE



PART No. 004P07 & 005P07

1	End Support 1 Main	PS 07
2	End Support 25/07/07	PS 07

All joints weld arround unless specified otherwise.
Fillet weld min leg=7mm

Fixing plate holes 20 mm to align with similar on soil bin

Cutting List

End	support 1 (Main)		
1	Box 100x100x3	1468	1
2	Box 100x100x3	1400	1
3	Box 100x100x3	1900	1
4	Plate 30x40x15		4

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LOW CARBON MILD STEEL

Main support Pad

1 of 1

004P07 & 005P07

Appendix 9 Baldor motor code

```
'Rolling test rig

Dim index As Integer

Dim cycles As Float , setspeed As Float

'wait for main power

Print "Checking main power... ",

Pause DRIVEBUSVOLTS > DRIVEBUSNOMINALVOLTS * 0.7

Print "OK."

Wait 1000

DRIVEENABLE(0) = _ON

Print "Move to home sensor."

SOFTLIMITMODE(0) = _emIGNORE

HOME(0) = _hmNEGATIVE_SWITCH

Pause IDLE(0)

Print "Home found."

'enable soft limits

SOFTLIMITMODE(0) = _emCRASH_STOP_DISABLE

Input "How many cycles ? ",cycles

Repeat

 Input "at speed (mm/s) ? ",setspeed

Until setspeed>=40 And setspeed <=300

'RUN !!

For index = 1 To Int(cycles)

 Print "Stroke ",index," of ",Int(cycles)

 'move forward

 SPEED(0) = setspeed

 MOVEA(0) = 1920

 GO(0)

 Pause InKey = 'y'

   'move back

 SPEED(0) = setspeed

 MOVEA(0) = 0

 GO(0)

 Pause IDLE(0)

 Next  Print "Test complete."  End
```

```
Startup
' Thursday, May 10, 2007
Define ALL = 0
Define SELECTED = 0
Define SERVOS = 0
Define DINBANKS = 0, 1, 2
Define DOUTBANKS = 0, 1, 2
Define ADCS = 0
Define ENCODERS = 0
Define AUXENCODERS = 0
' Abort any motion currently in progress
ABORT:Wait = 10
' Define loop times
LOOPTIME = 1000
' Define config modes for all axes
CONFIG[SELECTED] = _cfSERVO
' Initialize the axes
CANCELALL
DRIVEENABLE[SELECTED] = 0;
' Digital input configuration
INPUTMODE[DINBANKS] = 0, 0, 0 ' 0x0, 0x0, 0x0
INPUTACTIVELEVEL[DINBANKS] = 011111111, 01111111111, 01111111111 ' 0xff, 0x3ff, 0x3ff
INPUTPOSTRIGGER[DINBANKS] = 0, 0, 0 ' 0x0, 0x0, 0x0
INPUTNEGTRIGGER[DINBANKS] = 0, 0, 0 ' 0x0, 0x0, 0x0
' Analog input configuration
ADCMODE[ADCS] = 0
' Digital output configuration
GLOBALERROROUTPUT = -1
OUTPUTACTIVELEVEL[DOUTBANKS] = 0111, 011111, 01111111111 ' 0x7, 0x1f, 0x3ff
' Axis scaling
SCALEFACTOR[SELECTED] = 16384 * 10 / 200
' Axis Error parameters
ERRORINPUTMODE[SELECTED] = _emCRASH_STOP_DISABLE
ABORTMODE[SELECTED] = _emCRASH_STOP_DISABLE
LIMITMODE[SELECTED] = _emCRASH_STOP_DISABLE
```

```
SOFTLIMITMODE[SELECTED] = _emIGNORE

STOPINPUTMODE[SELECTED] = 3

SOFTLIMITFORWARD[SELECTED] = 1970

SOFTLIMITREVERSE[SELECTED] = -10

FOLERRORMODE[SERVOS] = _emCRASH_STOP_DISABLE

FOLERRORFATAL[SERVOS] = 4.07

' Axis Digital input events

ERRORINPUT[SELECTED] = -1

HOMEINPUT[SELECTED] = 0

STOPINPUT[SELECTED] = 1

LIMITFORWARDINPUT[SELECTED] = -1

LIMITREVERSEINPUT[SELECTED] = -1

RESETINPUT[SELECTED] = -1

' Axis Drive Output Enables

DRIVEENABLEOUTPUT[SELECTED] = -1

' Axis Tuning Parameters

KDERIV[SERVOS] = 0.00

KINT[SERVOS] = 0.00

KINTLIMIT[SERVOS] = 100.00

KINTMODE[SERVOS] = 0

KPROP[SERVOS] = 2.00

KVEL[SERVOS] = 0.00

KVELFF[SERVOS] = 1.88

KACCEL[SERVOS] = 0.00

' Axis Parameters

SPEED[SELECTED] = 1000

ACCEL[SELECTED] = 50

DECEL[SELECTED] = 100

ERRORDECEL[SELECTED] = 10000

SRAMP[SELECTED] = 0.00

MOVEBUFFERSIZE[SELECTED] = 2

HOMEBACKOFF[SELECTED] = 10.00

HOMESPEED[SELECTED] = 100

IDLEPOS[SERVOS] = 4.07

IDLEVEL[SERVOS] = 20.35  - End Startup
```

Appendix 10 Campbell data logger code for 6 pressure transducers

```
;(logger_21X)
*Table 1 Program
  01: 0.0125    Execution Interval (seconds)

1:  Volt (SE) (P1)
 1: 1         Reps
 2: 15        5000 mV Fast Range
 3: 16        SE Channel
 4: 1         Loc ( switch )
 5: 1.0       Mult
 6: 0.0       Offset

2:  If (X<=>F) (P89)
 1: 1         X Loc ( switch )
 2: 4         <
 3: 100       F
 4: 0         Go to end of Program Table

3:  Do (P86)
 1: 10        Set Output Flag High

4:  Ex-Del-Diff (P8)
 1: 6         Reps
 2: 13        50 mV Fast Range
 3: 1         DIFF Channel
 4: 1         Excite all reps w/Exchan 1
 5: 01        Delay (units 0.01 sec)
 6: 5000      mV Excitation
 7: 2         Loc ( pres_1  )
 8: 1.0       Mult
 9: 0.0       Offset

5:  Resolution (P78)
 1: 1         High Resolution

6:  Sample (P70)
 1: 6         Reps
 2: 2         Loc ( pres_1  )

7:  Time (P18)
 1: 0         Tenths of seconds into current minute (maximum 600)
 2: 0         Mod/By
 3: 8         Loc ( time  )

8:  Sample (P70)
 1: 1         Reps
 2: 8         Loc ( time   )

9:  Serial Out (P96)
 1: 12        Printer ASCII/9600 Baud

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines
End Program
```

Appendix 11 Roller specifications for rollers used in rolling experiments

Roller	**Width**	**Diam'**	**Roller mass**	**Drums**	**Load per drum**	**Load per m width**	**Roller effect**
	m	**m**	**kg**	**no.**	**kg**	**kg m^{-1}**	**no.**
Autoroller - front, no ballast	1.2	0.6	1740	2	870	725	1208
Autoroller - rear, no ballast	1.2	0.6	1740	2	870	725	1208
Autoroller - front, ballasted	1.2	0.6	2020	2	1010	842	1403
Autoroller - rear, ballasted	1.2	0.6	2020	2	1010	842	1403
Rolling rig	0.5	0.6	130	1	130	260	433
Rolling rig	0.5	0.6	220	1	220	440	733
Rolling rig	0.5	0.6	420	1	420	840	1400
Rolling rig	0.5	0.6	625	1	625	1250	2083
Rolling rig	0.5	1.0	130	1	130	260	260
Rolling rig	0.5	1.0	220	1	220	440	440
Rolling rig	0.5	1.0	420	1	420	840	840
Rolling rig	0.5	1.0	625	1	625	1250	1250

Appendix 12 Project funding budget (as at 31.07.08)

Rolling optimisation funding	Item	year 1	year 2	year 3	year 4	Total	Budget	Balance
maintenance grant		3500	3500	3500	3500	14000	14000	0
Equipment	*Roller*	4850				4850	10000	
	Test rig			3831	1242	5073		77
Materials	*soil*	915	3859			4774	16000	
	triaxial parts			2442		2442		
	misc	341	490	108	341	1280		
	plots		780			780		6724
Travel and subsistence		481.45	-356.05	567.74	210.58	903.72	4000	
								3096.28
Admin/courses	*MBA/EngD*	5000	1500	1500	1500	9500	0	
								-9500
Total		15087.5	9772.95	11948.7	6793.58	43602.7	44000	397.28

Appendix 13 ISEA Munich conference paper

Reprinted from: The Engineering of Sport 6, Volume 1: Developments for Sports. E F Moritz & S Haake (Eds.), 2006, Springer, NY, USA. ISBN-10: 0-387-31773-2, p 229-234

The Mechanical Behaviour of Cricket Soils During Preparation by Rolling

Peter Shipton, Iain James and Alex Vickers
Cranfield Centre for Sports Surfaces, Cranfield University, UK,
i.t.james@cranfield.ac.uk

Abstract. The nature of the ball – surface interaction in cricket has been identified as critical to the quality and safety of the sport. The requirement for even ball bounce and good pace from a clay loam soil cricket pitch has been successfully characterized and has been observed to be related to soil properties such as dry bulk density, moisture content and organic carbon content. To achieve the required mechanical properties, practitioners manage the compaction of a cricket pitch through the use of smooth steel-wheeled rollers. The relationship between moisture content and the compaction and shear strength was determined for a typical clay loam soil and was found to be significant. The effect of subsequent passes of 4.75 and 5.71 kN on soil dry bulk density was also determined in the soil dynamics laboratory. Maximum dry bulk density was achieved after 20 and 10 passes of each roller, respectively. The roller did not have a significant effect on dry bulk density below 50 mm in the profile.

1 Introduction

There are few sports where the ballistics of ball trajectory prior to, during and post interaction with the surface are as critical for the quality and safety of play as in cricket. The two key parameters, describing this interaction are known within the sport as 'pace' and 'bounce'; defined by James, Carré, and Haake, (2004) as the velocity and trajectory of the ball post impact with surface. For both the batting and fielding side to have an equal chance in the game, and for batsman safety, variation in pace and bounce of pitch should be 'predictable' i.e. within acceptable limits of play. Whilst these limits are subjective in their nature, the effect of adverse ball – surface interaction is apparent to players, officials and spectators of the game and will result in low scores, shortened games and risk of injury. Further, complete uniformity in pace and bounce will favour the batting team, desirable in short versions of the game where a result is guaranteed but less so in 4 and 5 day games where a result is dependent upon completed innings.

Variation in pace and bounce was studied by James et al, (2004) who developed methods of measuring and predicting variation in pace and bounce in UK cricket. The relationships among pace and bounce and soil physical/chemical parameters such as particle size distribution, dry bulk density (the oven-dry mass of soil in a known volume) and organic matter content were reported by Baker et al (2003), who determined that there was a positive correlation between pace and the dry bulk density and sand content of a soil, but there was a negative correlation between pace and moisture content, silt content and organic matter. Whilst established relationships of this type exist, these relationships observe the pitch in its 'match-ready condition', i.e. they do not inform the pitch construction or preparation process beyond the required final physical condition of the surface. Furthermore, these relationships are based upon soil-physical rather than soil-mechanical properties.

To achieve the required uniformity of surface mechanical properties, the soil is compacted using a steel smooth-wheeled roller. This aims to increase bulk density and shear strength through compaction and to produce a level, smooth surface. Whilst in a compacted, dry state a clay soil provides high mechanical stiffness and shear strength (a key property for resistance to wear), the shear strength of a clay soil is known to be highly sensitive to moisture content (Henkel, 1959). Therefore, during play, soil moisture content must be kept to a minimum. To achieve drying of the complete soil profile, grass growth and deep rooting are essential as water is removed through transpiration. Therefore bulk density and shear strength must not exceed critical values which prevent grass growth for extended periods of time. The requirements of a surface are bounded by a lower limit of sufficient surface shear strength and stiffness for pace, bounce and wear resistance, and an upper limit of shear strength for grass growth.

To translate any mechanical model into practical guidelines for the practitioner, the optimum soil moisture and duration for rolling, and how rolling practices affect surface mechanics must be investigated. This forms the key aim of a four year study by the authors to model the mechanical behaviour of cricket soils during preparation. This paper reports on the first year of this project which aimed to determine key mechanical properties of a typical soil used in cricket pitch construction in the UK and the behaviour of these soils during construction and compaction by a steel smooth-wheeled roller.

2 Materials and Methods

2.1 Test Soil Characterization and Selection

The soil (labelled *Cl30* here) was sourced from Essex, UK and had a particle size distribution of 30% sand, 40% silt, 30% clay. It is typical of soils used at elite and well resourced recreational levels of the game.

2.2 Determination of the Optimum Moisture Content for Compaction of Each Soil

All moisture contents in this paper are reported on a gravimetric (mass) basis. The optimum moisture content for compaction of the soils was determined using the 'Proctor Test' (Proctor, 1933). Soil specimens of a fixed bulk volume 929 ml, were prepared at a range of gravimetric moisture contents between 5 and 30%. Each specimen was constructed in 3 layers, each layer receiving 27 blows from a 4.5 kg hammer, dropped from a height of 450 mm. The resultant dry bulk density (ρ_b) of each specimen was determined by measuring the oven dry mass of the soil in a known volume. The proctor optimum moisture content for compaction was determined as the peak of the moisture content – dry bulk density curve.

2.2 Determination of the Shear Strength

Shear strength, the shear stress at failure of a test specimen was determined using two methods: the translational shear box and the quick, undrained triaxial shear test. For the translational shear box, specimens were prepared at 6% and 18% moisture content. The 60 x 60 x 20 mm samples were then placed in the translational shear box and subjected to an incremental strain at a rate of 1.25 mm/min. The shear stress at failure was determined for a range of normal stresses between 15.7 kN/m^2 and 70.2 kN/m^2.

For the quick, undrained triaxial shear test, 38 mm diameter x 72 mm length cylindrical samples were failed in shear at total confining stresses of 35, 69, 103 and 138 kN/m^2, at a strain rate of 1.5 mm/min. Samples were prepared at 15, 18 and 23% and tests were conducted in triplicate. In both methods, dry bulk density was constant at 1500 kg m^{-3}.

Linear models of soil failure at a shear stress (τ, kN m^{-2}), as a function of normal stress (σ, kN m^{-2}) were determined by the Coulomb theory of soil failure (Lamb & Whitman, 1969).

$$\tau = c + \sigma \tan\phi \qquad (1)$$

This model, described in Eq. 1, was determined by linear regression in the translational shear box test and by the construction of Mohr's circles for the triaxial test. Mean values of cohesion (c, kN m^{-2}) and internal angle of friction (ϕ, degrees) were analyzed by ANOVA.

2.3 The Effect of Successive Passes of a Roller on Dry Bulk Density

A test surface of *Cl30* soil (10 m length, 1.8 m width, 0.2 m depth) was constructed in the Cranfield University Soil Dynamics Laboratory in 50 mm compacted layers. Initial ρ_b was 1200 kg m^{-3} at a moisture content of 20.5%. A smooth steel-wheeled roller, typical of those used in the preparation on cricket pitches (diameter 0.3 m, width 1.2 m), was towed at two speeds, 0.28 and 0.56 m s^{-1} over the soil surface. The experiment was conducted at roller weights of 4.75 and 7.51 kN.

ρ_b was measured for subsequent passes of the roller at 50, 100 and 150 mm depths within the profile. The effect of roller weight on bulk density at each depth was determined by ANOVA.

3 Results

3.1 Compaction and moisture content

In the compaction test, there was a characteristic increase to a maximum, and then decrease in dry bulk density as moisture content was increased (Fig. 1). A significantly greater maximum ρ_b was achieved with the heavier hammer (1850 kg m^{-3} at a moisture content of 15%) than with the lighter hammer (1650 kg m^{-3} at 20%). The difference between hammers was expected due to the increased work done on the soil

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from the greater mass and this is typical of proctor test results. Beyond maximum ρ_b, compaction was limited by the pore water in the soil and thus the curves were similar from 20% moisture content.

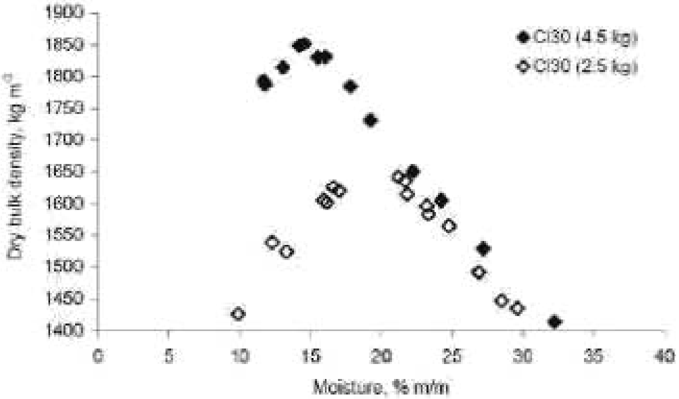

Fig. 1. Proctor compaction test results for the Cl30 soil with a 2.5 kg & 4.5 kg hammer

3.2 Shear strength parameters

Table 1. Mohr-Coulomb shear strength parameters for the *Cl30* soil

Soil	Gravimetric moisture content, %	Test method	Cohesion (c), kN m^{-2}	Angle int. friction (ϕ), degrees
Cl30	8	TSB	<0.1	51.8
Cl30	15	TSB	30.8	41.1
Cl30	15	QTxS	34.2	33.2
Cl30	18	QTxS	27.2	19.4
Cl30	23	QTxS	31.6	5.9

TSB – translational shear box; QTxS – quick undrained triaxial shear

Variation among cohesion (c) and internal friction angles (ϕ) is illustrated in Table 1. In the translational shear box experiment, c was significantly greater at 15% than 8% moisture content ($p<0.05$). In the triaxial shear experiment, there was a significant decrease in ϕ as moisture content increased ($p<0.05$), due to lubrication by soil water. The liquid limit of this soil was determined to be 20%. Whilst there was a significant relationship between c and moisture content ($p< 0.05$), it was not consistent. The only direct comparison between the two test methods was for the *Cl30* soil at 15%; there was no significant difference in c and ϕ between methods.

3.3 The effect of subsequent passes of a roller on soil bulk density

Rolling increased ρ_b significantly in the first 0-50 mm of the profile. At 50-150 mm there was no consistent pattern of ρ_b increase with successive passes of either roller. The increase in ρ_b at 0-50 m with subsequent passes of a roller was characterized by an increase to a maximum for the first passes and then a plateau for subsequent passes. For the 4.75 kN roller this peak occurred at 1470 kg m^{-3} after 20 passes; for the 7.51 kN roller the peak was 1540 kg m^{-3} after 10 passes.

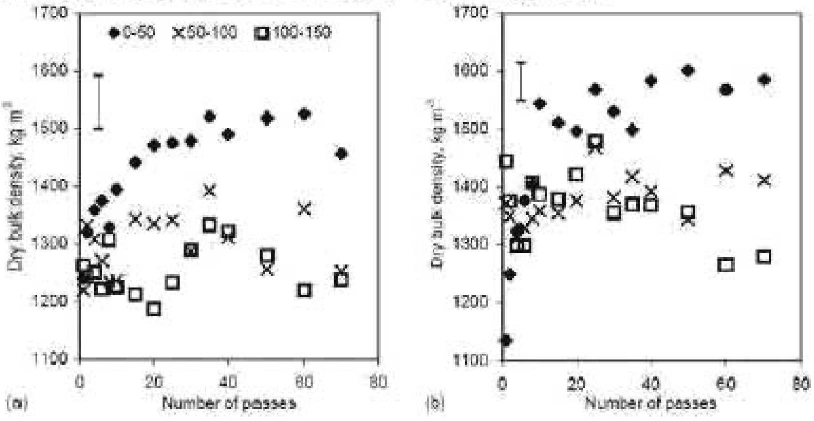

Fig. 2. Mean dry bulk density of *Cl30* at 0-150 mm depth, following successive passes of a 4.75 kN (a) and 7.51 kN (b) smooth steel wheeled roller at 20% gravimetric moisture content. Error bars represent the LSD at p=0.05

4 Discussion

The results of both the compaction and shear strength analyses illustrate the sensitivity of both properties to moisture content. Depending upon the magnitude of the load applied, there is an optimum moisture content for the compaction of the soil and a maximum bulk density that can be produced. For effective rolling of cricket pitches soils should be as close to the optimum moisture content for the load being applied.

In compaction, an increase in moisture content eventually reduces the effect of normal stresses due to the low compressibility of water. In shear, an increase in moisture content was shown to initially increase shear strength due to an increase in cohesion caused by the interaction between clay particles and thin films of water. As soil moisture content increased above 15%, however, cohesion did not increase but friction between soil particles reduced significantly, reducing soil strength.

When rolling cricket pitches the shear strength of the soil has to be exceeded by the rolling stresses for compaction to be achieved. Whilst the principal objective is normal loading of the soil, horizontal stresses are inevitable and are considerable in driven rollers where torque can cause wheel slip in excess of shear strength. In these conditions the soil is at significant risk of undesirable surface damage that could have an adverse effect on ball pace and bounce.

The data in Fig. 1 showed that maximum compaction occurred with the greater load at 15%, which coincides with the maximum shear strength of the soils in Table 1. The data in Fig. 2, however, showed that even the heaviest roller (some rollers currently in use in the field may exceed this weight) did not cause compaction beyond 1540 kg m^{-3}, less than the maximum with the lighter hammer in Fig. 1 at similar moisture contents. Field data have shown that ρ_b can reach the 1850 kg m^{-3} observed in Fig. 1 due to consolidation from removal of water over longer periods of time. At such a value of ρ_b, air filled porosity can be as low as 5%, to reduce porosity further will limit grass growth and the effect of grass on both moisture content and shear strength by root reinforcement has not been considered here.

It is also important to note that maximum compaction was achieved after only 20 passes of a 4.75 kN roller and 10 passes of a 7.51 kN roller. If this result is observed in similar experiments with grass surfaces, currently in progress, then it will have a significant effect in reducing the time spent rolling cricket pitches in practice. Also, the roller was only effective in compacting the first 50 mm of the profile. This has direct implications for the construction of cricket pitches where it is apparent that only consolidation will increase the bulk density of the soil below 50 mm depth. It should be noted that the critical compacted surface depth for ball interaction is not well understood or quantified in the literature.

5 Conclusion

The maximum dry bulk density (ρ_b) in a proctor compaction test of a typical soil used in first class cricket in the UK, was 1850 kg m^{-3} at 15% gravimetric moisture content using a 4.5 kg hammer and 1650 kg m^{-3} at 20% using a 2.5 kg hammer. The shear strength of the soil was greater at 15% than 18 and 23%. As soil moisture content increased from 8 to 15 %, cohesion increased significantly, but was not significantly different from 15 to 23%. Internal friction decreased significantly from 8 to 23% due to lubrication of soil particles by water.

It was shown that after 20 passes of a 4.75 kN roller, typical of the type used in cricket pitch preparation, ρ_b increased significantly from 1200 to 1470 kg m^{-3} but that there was no significant increase for subsequent passes. Likewise, for a 7.51 kN roller, a maximum bulk density of 1540 kg m^{-3} was achieved after only 10 passes.

These data form part of the development of a model to improve the construction and preparation of cricket pitches.

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Appendix 14 ISEA Biarritz conference paper

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The dynamic compaction of cricket soils for pitch preparation

Peter Shipton[1] and Iain James[1]

[1] School of Applied Sciences, Cranfield University, UK,
p.m.r.shipton.s03@cranfield.ac.uk; i.t.james@cranfield.ac.uk

Topics: Cricket pitch preparation

Abstract. In cricket, where a hard leather ball is bounced onto a natural turf, clay soil pitch between the 'bowler' and the 'batsman' at speeds of 20 to 160 km h^{-1}, the ball-surface interaction is critical. This interaction is a function of the mechanics of the surface, which in turn are affected by soil packing (bulk density) and moisture content in the critical top 100 mm of the profile. To achieve the required mechanical properties of the pitch, the surface is consolidated with a smooth wheeled, steel roller at optimum moisture for compaction. This paper describes initial results from laboratory scale tests using an apparatus designed to investigate the effect of key design and operating variables for the roller (mass, roller diameter, forward speed) and environmental factors (soil type, moisture content, grass) on surface consolidation with depth through the facilitate profile.

Keywords: cricket; soil mechanics; playability

1 Introduction

The nature of the importance of the ball-surface interaction in cricket is described in James, Carré, and Haake, (2004). This interaction is controlled by the mechanical properties of the clay loam soil surface, which are manipulated using a smooth-wheeled steel roller (Shipton, James, and Vickers, 2006). The aim of this process is to achieve a flat, consolidated surface that maximizes soil strength by increasing soil particle packing and minimizing moisture content, but still permits grass growth to aid the playing performance of the pitch, reinforce the soil with the grass root network and facilitate drying of the soil through transpiration. The critical soil depth for playability of a soil profile ranges from the top 75 to the top 100 mm (Adams & Gibbs, 1994; Baker et al., 2003). The rolling of cricket pitches is carried out prior to the start of the playing season and then immediately before a pitch is used for play. A survey of practices across England and Wales revealed a variation of 1000% in terms of the time spent rolling at different cricket facilities, highlighting the need for an improved understanding and an optimization of the rolling process (unpublished data, Cranfield University).

The aim when rolling with a smooth wheeled roller is to increase dry bulk density (ρ_d). This is achieved in conjunction with shrinkage of the soil during natural drying of the soil profile. The soil moisture content required for efficient compaction is greater than for optimum playability (Shipton, James, and Vickers, 2006) thus a drying period after rolling and before play is necessary.

To achieve the required soil density the load applied to the soil needs to be sufficient to overcome the soil structural resistance to the applied stress. This resistance is largely a result of soil mineralogy, density and moisture content. The magnitude and direction of the applied stress is a function of a number of roller design parameters: contact area – governed by roller diameter and width, roller mass and operating speed.
This study provides data from laboratory-scale experiments investigating different roller design parameters using an instrumented rolling rig. This approach provides optimized design parameters for roller design and operation.

2 Materials and Methods

2.1 Instrumented Rolling Rig

The rolling rig (Figure 1) comprises a 3500 mm x 500 mm x 350 mm steel tank, filled with the test soil. At the mid-way position along the length of the tank a 600 mm x 500 mm viewing window allows investigation of soil movement through the soil profile (y:z plane). Roller diameters from 200 mm to 1000 mm can be mounted in the frame which allows the roller to float and can be towed in both directions using a linear transmission and positioning device (HepcoMotion, Devon, UK) powered by an AC servomotor/drive system (Baldor, Bristol, UK). Forward speed can be controlled at 20 mm/s to 1000 mm/s.

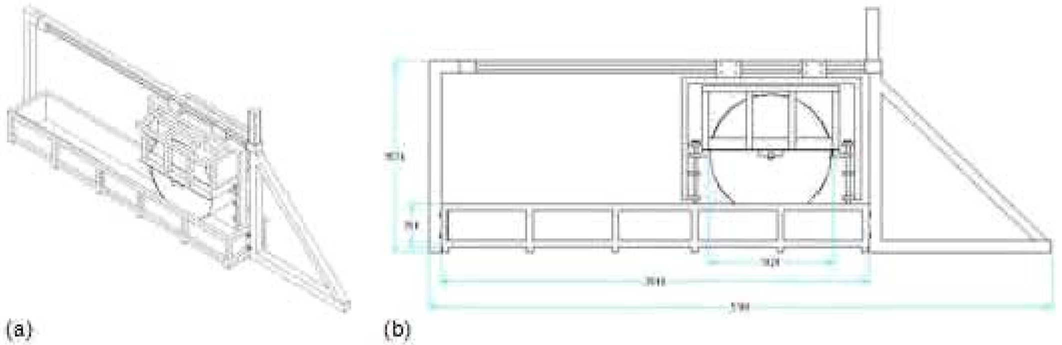

Figure 1 Cricket rolling rig – (a) 3-D schematic and (b) side view

The most common type of roller used in cricket has two rollers of 600 mm diameter and a mass of 2000 kg. The results presented in this paper are for a roller with a diameter of 600 mm driven at 84 mm/s and operated at four passes of five ballasts (130; 220; 310; 400; 490; 580 kg) applied consecutively. A period of 10 minutes between roller passes was allowed to facilitate elastic recovery and to emulate cricket pitch preparation requirements. The maximum load is equivalent to a 3000 kg, 2 drum roller.

The soil used was a clay loam soil from Essex, UK (30% sand; 40% silt; 30% clay). It is typical of soils used at elite and well resourced recreational levels of the game. The soil was passed through a 5 mm sieve and water added to give the required gravimetric moisture content of 20% and was evenly packed to give an initial density of 1.2 g cm^{-3} to a depth of 250 mm. The prepared profile was left for 24 hrs to ensure equilibration of moisture.

Applied pressure at depth was recorded using three ceramic membrane pressure transducers of 18 mm diameter mounted in 25 mm diameter tubular aluminium housings at depths of 25 mm, 50 mm and 80 mm in a method similar to James, Dixon, Blackburn, and Pettican (2006).. Each transducer was logged at 10 Hz.

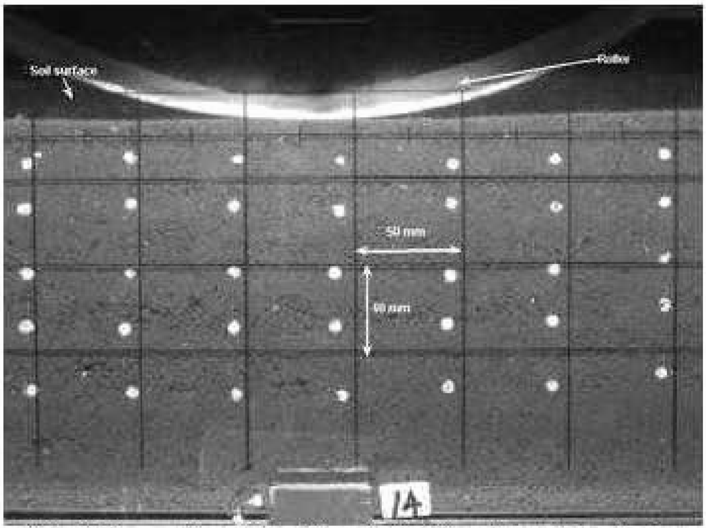

Figure 2 Cross section of soil profile as imaged through the viewing window.

An array of 6 mm diameter markers was placed in the soil to be viewed through the window at depths of 25 mm, 50 mm, 80 mm, 100 mm and 140 mm, with seven markers at each depth (Figure 2). Their movement under load was recorded at 30 fps using a Fujifilm finepix S9600 digital camera. The horizontal (y) and vertical (z) components of movement of the marker centroids was determined using image processing scripts in Matlab (Mathworks, Cambridge, UK).

Mean data for pressure and displacement with depth are presented for four consecutive passes of the roller at 490 kg load and for the first pass of each roller load. Displacement data is presented as R, max dy and max dz as defined in Figure 3.

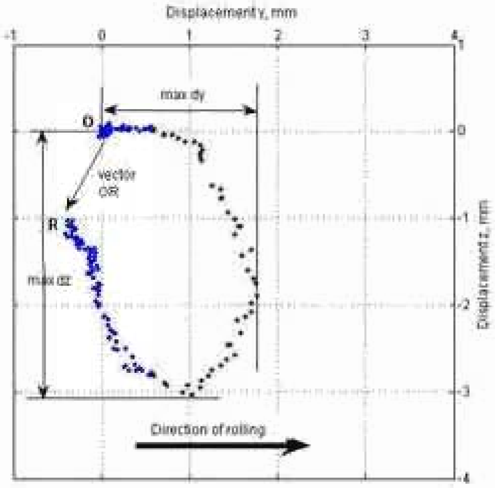

Figure 3 Clockwise trace of marker movement with left-to-right rolling (25 mm depth, 220 kg load). The three recorded parameters are shown, R: the final permanent displacement; max dy, the maximum horizontal displacement; max dz, the maximum vertical displacement

3 Results and Discussion

3.1 Pressure – Load – Depth relationship

At 25 mm, pressure ranged from 150 to 450 kPa and increased with load (Figure 4). At 50 mm, a similar relationship between pressure and load was observed but the magnitude was between 100 and 150 kPa for all ballast loads. At 80 mm, a constant pressure of 50 kPa was observed, irrespective of load. These results are as expected and tie with the data presented in Shipton, James and Vickers (2006) which determined little effective compaction below 50 mm with similar roller configurations.

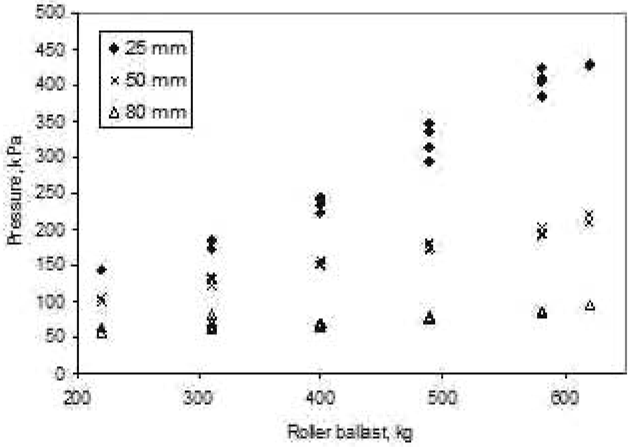

Figure 4 Mean pressure with increasing roller load, at depths of 25, 50 and 80 mm within a clay loam soil

3.2 Displacement –depth – load

Generally, the cumulative resultant displacement from the initial condition to the final loading, i.e. the permanent displacement of the marker from O to R increased with roller load, and with depth (Figure 5). At 130 and 220 kg, displacement was minimal; at greater loads the soil was moved downwards and forwards to a greater extent. For example at 25 mm depth, with the 580 kg ballast, the soil was moved downwards by -4.5 mm and forwards by 0.3 mm. As depth increased for the same load, forward displacement was similar, but vertical displacement was reduced to -2 mm.

The maximum movement of the markers in any pass reflects the elasticity of the bulk soil with maximum vertical displacements of 30 mm and 18 mm horizontally (Figure 5). Again, the maximum displacements increased with load, and decreased significantly with depth.

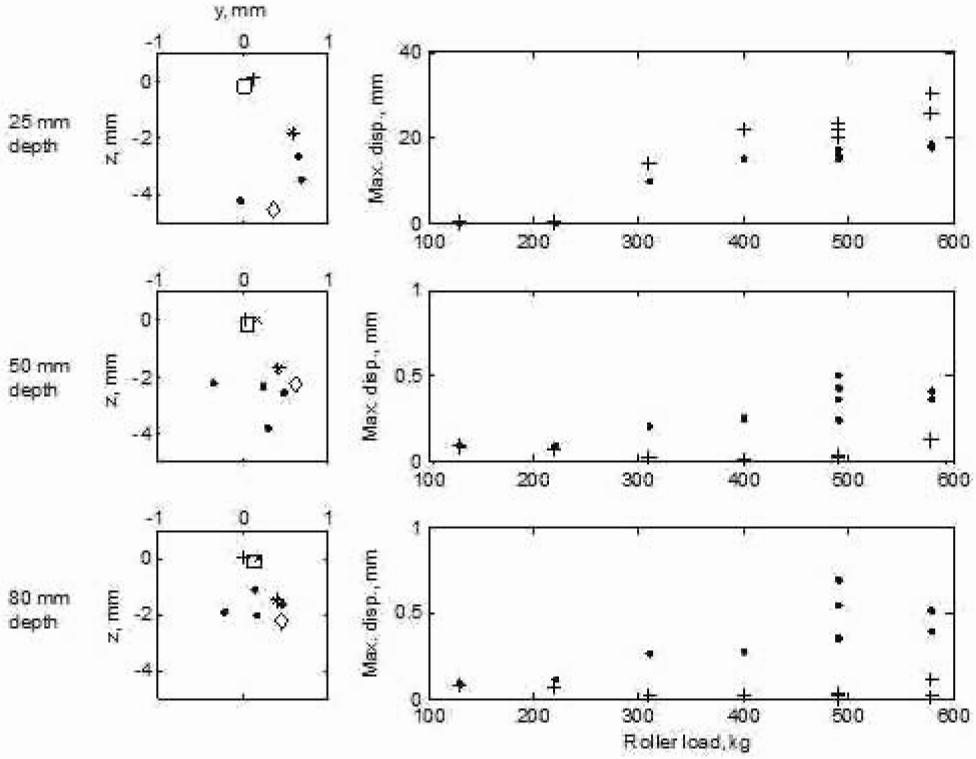

Figure 5 Displacement at depths related to sensor depths (25, 50 and 80 mm). Left hand column: position of R in y:z for first pass of different loads: + 130 kg, □ 220 kg, × 310 kg, ☆ 400 kg, • 490 kg (4 passes), ◊ 580 kg. Right hand column max dy (•) and max dz (+).

3.3 Implications for rolling

Results show pressure and displacement reduce with depth, with minimal displacement at the lowest depths measured. Increasing load indicates large increases in pressure at the top of the profile but a reduced increase with depth resulting in a relatively greater compaction near to the surface. Even compaction from rolling throughout a 100 mm cricket pitch profile is therefore unlikely with this diameter of roller and a maximum 3t load on a typical roller.

Displacement reduces with consecutive roller passes indicating that after four passes the gain in ρ_b is relatively insignificant. The current practice by most cricket groundsmen of multiple roller passes would appear to be ineffectual in achieving greater ρ_b and additional roller passes would only be appropriate after an increase in roller weight or a change in soil moisture. These results also indicate that heavier cricket rollers than is currently normal i.e. >2.5 ton, would be advantageous in increasing ρ_b to a greater depth.

The horizontal component of movement is important as this is thought to cause shearing of roots in the soil, leading to the adverse phenomenon of 'root breaks' where a sheared layer between 25 and 50 mm allows dense horizontal root growth, creating a 'spring' in the cricket pitch profile. This technique will be used to explore this hypothesis further, and future studies will include vertical reinforcement from live grass roots, which is expected to reduce this horizontal component. Future work will also investigate moisture content and roller diameter variables.

4 Conclusions

The instrumented rolling rig provides a tool for the development of steel smooth-wheeled rollers for cricket pitch preparation in a controlled environment. The resultant data, which in this case show that pressure at 80 mm is negligible, even with relatively heavy rollers is significant in understanding the role of rolling in pitch consolidation. To increase density throughout the whole profile requires effective drying by the plant – it cannot be achieved by rolling alone. The horizontal component of deformation is considered significant and should be minimised in the rolling of cricket pitches. Further investigation will combine this data with field data in the form of a model to deliver optimised parameters for cricket pitch rolling and preparation.

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