Loughborough University
Centre for Innovative and Collaborative Construction Engineering

Development of a Turf Stability Assessment Method for Sports Surfaces

Frazer Dean Anderson

Labosport UK Ltd
Unit 3, Aerial Way
Hucknall, Nottingham
NG15 6DW

Centre for Innovative and Collaborative Construction Engineering
Department Architecture, Building and Civil Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

DEVELOPMENT OF A TURF STABILITY ASSESSMENT METHOD FOR SPORTS SURFACES

By
Frazer Dean Anderson

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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Labosport UK Ltd
Unit 3, Aerial Way
Hucknall, Nottingham
NG15 6DW

Centre for Innovative and Collaborative Construction Engineering
Architecture, Building and Civil Engineering
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I would like to thank my four supervisors: Paul Fleming, Paul Sherratt, Colin Young and Kathryn Severn. Each supervisor assisted me to different degrees throughout the Engineering Doctorate (EngD) process, playing key roles in developing the project from its initial conception to the final stages.

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Moreover, I thank to Gareth Philips, Charles Henderson and Gary Owen of Professional Sportsturf Design Ltd, Agronomists that educated me in agronomic studies and supported the research.

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Lastly thank you to all the people I met on my EngD journey. You offered me some of the most memorable years at Loughborough University that I will forever cherish.

Slàinte Mhath!

ABSTRACT

The majority of outdoor sports are played on natural turf pitches. Throughout the playing season, a pitch has continual player interaction, which, during periods of sustained unfavourable conditions, can cause the turf to tear up (shear) under player contact. This is most evident in Rugby Union scrummages, which create deep divots in the turf and rootzone that reduce player safety and are criticised by the media. However, little is known of the turf/rootzone strength to depth, termed 'shear stability' in this thesis, and there is currently no appropriate means to test this property.

In order to explore the shear stability of turf, a device was designed and developed. The prototype device, termed the 'Shear Tester', underwent trial, validation and several redesigns until it was deemed suitable to investigate turf shear stability. A range of natural and hybrid constructions and laboratory-controlled samples were investigated, and the key variables found to influence the shear stability were grass rooting, water content and rootzone density.

Clay-rich rootzone stability was found to be mainly dependent on water content and density. Sand-based rootzones in general demonstrated low shear stability and relied heavily on grass presence or fibres in the rootzone to provide suitable stability. Increasing shear stability was observed for reinforced rootzone, carpeted constructions and injected synthetic constructions, respectively. These hybrid (carpet-based or reinforced) systems were less affected by water content and density than natural systems. Grass establishment in these constructions further increased their stability. The test pins used by the device found that the shorter (50 mm) pin effectively measured near-surface strength and any inclusion of grass rooting or hybrid materials. The longer (100 mm) pin measured the stability of deeper rootzones. Future development will refine the device test method to provide more repeatable pin results that are more replicable to players interaction on the surface.

KEY WORDS

Natural Sports Surfaces, Sports Turf Construction, Soil Texture, Surface Performance Testing, Shear Stability, Rootzone, Hybrid Turf Construction

PREFACE

This thesis details the study undertaken between 2014 and 2018 meeting the requirements to achieve the Engineering Doctorate (EngD) at Loughborough University's Centre for Innovation and Collaborative Construction Engineering (CICE). The research was funded by the Engineering and Physical Sciences Research Council (EPSRC) and the sponsoring company Labosport UK Ltd.

The EngD postgraduate qualification offered a larger industry involvement compared with a typical PhD. The EngD student worked within the sponsor company undertaking real-world projects for the company, which met the themes of the established EngD project.

The EngD had four supervisors, two industrial (Labosport UK Ltd) and two academic (Loughborough University). For both the academic and industrial supervisor, one maintained either a leading or supporting supervisory role throughout the project.

The work packages for the project were created and steered by the industrial supervisor. The important information from the work packages was extracted to publications and relayed to the industrial supervisors in monthly progress meetings. A remit of the EngD detailed that a minimum of two peer-reviewed conference papers and one journal paper must be published and enclosed in the thesis. Three papers were produced; two conference papers and one journal paper. These are referenced throughout the text as Papers 1 – 3, and the full papers are reproduced in appendices C – E.

ACRONYMS USED / ABBREVIATIONS

3G	Third Generation
AAA	Advanced Artificial Athlete
ASTM	American Society for Testing and Materials
BS	British Standard
CICE	Centre for Innovation and Collaborative Construction Engineering
CIH	Clegg Impact Hammer
DP	Decimal Places
EN	European Standard
EngD	Engineering Doctorate
EPRSC	Engineering and Physical Sciences Research Council
ER	Energy Restitution
FIFA	The Fédération Internationale de Football Association
FR	Force Reduction
GRF	Ground Reaction Force
HDH	Hoof Drop Hammer
HP	Hand Pull
ISO	International Organization for Standardization
MK I/II	Mark One/Two
PP	Polypropylene
PQS	Performance Quality Standard
PSD	Particle Size Distribution
RTD	Rotational Traction Device
RWC	Rugby World Cup
TDR	Time Domain Reflectometry
VD	Vertical Deformation

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LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1 (SEE APPENDIX C)

Anderson, F.D., Fleming, P., Sherratt, P. and Severn, K., 2015. Investigating shear stability of rugby union natural turf pitches. Procedia Engineering, 112, pp.273-278.

PAPER 2 (SEE APPENDIX D)

Anderson, F.D., Fleming, P., Sherratt, P. and Severn, K., 2016. Design and development of a novel natural turf shear stability tester. Procedia engineering, 147, pp.842-847.

PAPER 3 (SEE APPENDIX E)

Anderson, F.D., Fleming, P.R., Sherratt, P.J. and Severn, K., 2018. Novel field equipment for assessing the stability of natural and hybrid turfs. Sports Engineering, pp.1-11. …

1 INTRODUCTION

1.1 RESEARCH INTRODUCTION

Natural turf sports pitches are commonly used at community and elite level for many sports. Variations in soil textures of the rootzone (clay/sandy) dictates the mechanical properties. It is commonly observed that clay rich turf rootzones exhibit poorer mechanical properties with increasing water content. This is most evident through the winter months with cold temperatures and high precipitation relative to the summer. Poorer quality turf and high levels of player interaction with the pitch ('traffic' intensity and frequency) contribute to turf damage, including loss of grass cover, poor drainage and tears (divots) in the turf surface (James, 2015). Natural turf technology has advanced in more recent years, especially at elite level, reducing clay content and introducing higher sand content for better drainage and increased playability, and improved maintenance practices to aid recovery (James, 2015). Although improvements have been made, turf surfaces are still commonly observed to experience inadequate wear resistance and insufficient strength (see Figure 1) during intensive player interaction (James, 2015). This damage can create an uneven surface or reduce traction further, leading to a higher risk of player injury (Caple, 2011; Serensits, McNitt and Petrunak, 2011).

In sports such as rugby and football, a player's foot creates high horizontal shear forces (torsional and linear) between the boot and the surface. In the modern professional era, significant investment is made in sports to enable athletes to perform to their full potential: This is evident from developments in athlete nutrition, training and technology (Haake, 2009). These developments have made athletes body shapes optimal to their sport, subsequently increasing forces and further placing strain on the natural sports surfaces.

Examples of inadequate surface stability in natural turf pitches have been reported in the media recently during football internationals, such as the UEFA European Championship 2016

(Morgan, 2016) and the Rugby Union Super 18 Rugby competition (Windley, 2016). Hybrid turf pitches (i.e. natural turf reinforced with plastic fibres) and artificial (fully synthetic) turf constructions have increased their share of the elite market with the rationale that they are more wear resistant and more stable, thus more suited to more intensive use, and therefore have been accepted at the highest levels of these sports (e.g. Guinness Pro 14 (Barry, 2016) and the English Rugby Premiership (ITV News, 2014)).

Figure 1 – St James Park (Newcastle-upon-Tyne, UK), during the Rugby World Cup 2015. The turf was torn out from the forces of the rugby scrummage: (a) showing the repeat scrum moved because of turf damage: (b) the player-generated forces from the engaged scrum created large divots and tears in the turf and rootzone

Anecdotal observations from ground staff point to failures of the turf systems underneath the rooted grass plant in many cases, at depths of up to 100 mm. Therefore, to support the professional game as a spectacle and for player safety, the natural turf pitches ideally must be prepared to an acceptable standard, with the turf's ability to survive the forces applied to it ideally both measured and understood. Minimal limits in pitch quality have been monitored with surface performance tests with the PQS Framework (The Institute of Groundsmanship, 2001) in the past and more recently Labosport UK Ltd has introduced their own test (Scoreplay™) to determine sports turf pitch performance and agronomic quality to providing a more insightful indication of turf quality. Generally, if a pitch has 'good' shear stability properties then there will be no noticeable or minimal damage to the surface and turf. 'Poor' shear stability will produce evident damage, as seen in Figure 1.

However, the stability of the turf, i.e. its resistance to shearing, is thought to be influenced by a complex interacting matrix of the different soil materials, organic plant matter, and water conditions (Clarke and Carré, 2017). Mechanical tests exist for measuring the boot-related traction (linear and rotational) of a sport surface; however, they all have their limitations. In particular, these tests are focused on the near-surface resistance to shearing for turf around standard length (13 mm) studs. At present, however, no industry standard test exists for directly assessing the stability of turf deeper into the rootzone.

This widely reported and little understood occurrence of deeper shear failures of the sports natural turfgrass and the lack of a method to measure it determined a need for an effective assessment. Labosport UK Ltd therefore initiated the EngD and the subsequent aims and objectives of the projects. It was proposed that the project would create a device that could assess natural sports turf's stability to better evaluate the shear strength of sports surfaces deeper in the turf, preventing the common failures seen in media. The device would also enable improvement in the versatility of the Scoreplay™ pitch quality test.

1.2 BACKGROUND TO THE RESEARCH

1.2.1 INTRODUCTION TO NATURAL AND HYBRID SPORTS TURF

Natural turfgrass sports surfaces have been utilised since the early ages of modern sport. Current natural sports turf surface is a complex system integrating the plant with a granular soil rootzone that varies in response to environmental variables – detailed description in James (2015). Prior to the 1980s, turfgrass was predominantly clay-based (Young and Henderson, 2016), which had a tendency in cold wet winter months to becoming muddied, losing grass coverage and deforming to create divots (James, 2011, 2015; Serensits, McNitt and Petrunak, 2011). These characteristics used to be accepted as ‘part of the game’ but as technologies in apparel and player performance have improved (Haake, 2009), combined with the high stakes of modern professional sport and the scrutiny of media, the sports turf has become a key component in performance.

In view of this, expert groundkeeping, and research was essential in order to improve and maintain surface quality. In the 1980s, introduction of sands to clay-based turfgrass increased drainage significantly, and increases in sand soil texture up to 90 % (sand:clay) were used to exploit this characteristic (Beard, 1973; Arthur, 1997; Guisasola, 2008). However, when at a high percentage, sand-based constructions tended to decrease in surface stability and grass plant health (Stiles *et al.,* 2009; Wijk, 2013). Therefore, in order to increase stability, either the correct sand clay mix was required or alternatively hybrid constructions were used.

It is common place that modern natural turf grows *in-situ* onto a fully prepared rootzone (taking several months to fully establish) or, alternatively (and common at elite sporting stadia venues), a specialist supplier cultivates a turf construction which is imported and laid onto a prepared base. For the latter method the imported turf sections need time to establish rooting to depth and knit together with the subsoil base to provide surface stability.

The alternative hybrid constructions include synthetic (generally plastic) and natural components with the notion that they supply increased strength to the sports turf (McNitt and Landschoot, 2003; Sherratt, Street and Gardner, 2005). These are detailed in Table 1, and first appeared in the 1980s with reinforced surfaces that incorporated synthetic elements into the turfgrass rootzone. The 1990s saw *in-situ* hybrid injected synthetic constructions which vertically placed fibres throughout the turf and rootzone. Further, in 2000s, carpeted hybrid constructions were introduced that resemble third generation (3G) artificial turf and were either inserted into the natural turf rootzone or as part imported turf sections (Young and Henderson, 2016).

Table 1 – The evolution of surfaces, adapted from the Young and Henderson (2016)

Evolution of Surfaces								
Natural	Clay- Based			Increased sand ratio mix becomes popular				?
Reinforced				First reinforced rootzone			Growth in hybrid and reinforced systems	
Hybrid					First injected synthetic hybrid (*in-situ*)	First carpet-based hybrid		
Synthetic		Original synthetic turf (Astroturf™)	2G synthetic turf (sand infill)		3G synthetic turf (sand/rubber infill)	3G synthetic turf (natural infill)		
Year	Pre 1960	1960s	1970s	1980s	1990s	2000s	2010s	2020s

The market for sports pitch construction is vast and the hybrid turf is increasing its share (detailed in Young and Henderson, (2016)). In previous years hybrid constructions were only available to the elite/professional level because of the high costs of installation and maintenance (Table 2) (James, Hann and Godwin, 2007). However, with the growing market there has been a large increase in suppliers and products available for hybrid constructions. This has produced some constructions at a suitable budget to allow community and mid-level organisations to obtain a hybrid construction. Although possessing a greater share, the different hybrid constructions types have limited readily accessible research available on their surface properties compared with natural constructions. Moreover, some suppliers, namely those originally trading in artificial turf, do not possess an effective understanding of the principles of natural turf fields when designing a product. Therefore, the industry would benefit from greater understanding of hybrid sports pitch qualities relative to natural turf and if they can provide performance and safety to players.

Table 2 – Typical installation cost adapted from Young and Henderson (2016)

	Full Synthetic	Reinforced Rootzone	Carpet Hybrid	Injected Synthetic Hybrid	Sand-based
Initial cost (£)	550,000	250,000	280,000	850,000	75,000
Maintenance per year (£)	3000	25,000	27,000	35,000	9000
Labour per year (£)	6000	17,500	17,500	20,000	8500
7-year cost (£)	613000	547,500	591,500	1,235,000	197,500
Hour of use (year)	14,000	4,500	5,670	7,560	1,134
Cost per hour use (£)	44	122	104	163	174

1.2.2 STABILITY OF SPORTS TURF

Shear stability of turfgrass can be defined by a measure of resistance of the turf when it is placed under mechanical shear stress or force. There are three different shear stability failures that are seen to occur from interaction of the turf and player. In the first case detailed in Figure 2a the studs of the boot interact with the turf in the near-surface and the turf may either have enough shear stability or the turf rips away and boot movement occurs. For this near-surface failure, the Rotational Traction Device (RTD) (detailed in Section 3.6.1) can assess the shear stability. The second type of failure is witnessed during a sports turf interaction with a single boot (Figure 2b). In this case, the failure is identified when a clear separation of the turf sward and/or soil rootzone occurs from the rest of the sports surface from interaction with the player's foot, creating a divot or pulling a section of the grass plant and soil rootzone from its set location. In this case, the instability is localised to the boot; however, the third failure witnessed (Figure 2c) occurs where multiple players interacting with the surface and create a divot pulling a larger and deeper section of the turf and rootzone area from location. For the failures in Figure 2b and

2c this tearing of the turf/rootzone has been witnessed deep into the construction, with agronomists theorising a weak ‘failure zone’ underneath the turf present somewhere to a 100 mm depth. This failure zone is suggested to be roughly 50 mm for the individual player/surface interaction and 100 mm for the combined player/surface interaction. There is minimal research available on the causes of this phenomenon and unlike the near near-surface shear stability interaction there is not currently a specified device to measure the deeper failures in the turfgrass.

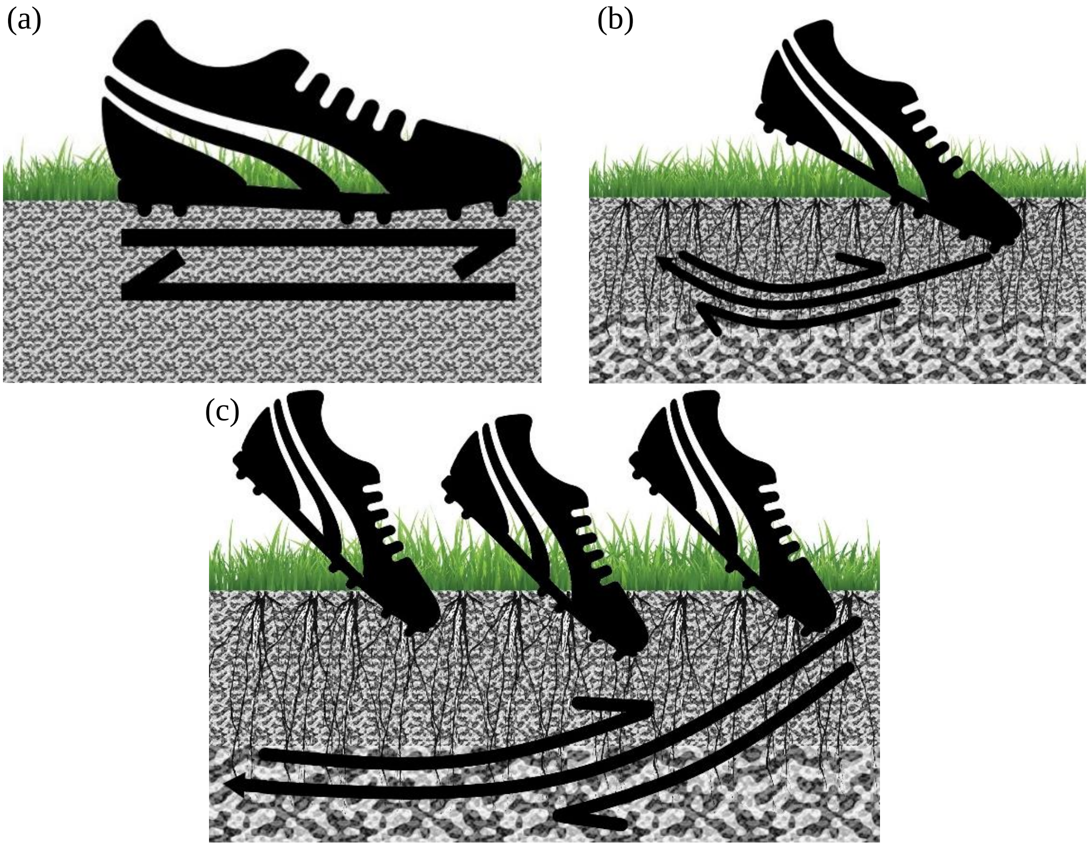


Figure 2 – Diagram showing foot/turf interaction for (a) near-surface shear stability, (b) localised deeper shear stability and (c) deeper shear stability across a larger area

As detailed previously, this deep shear instability is witnesssed largely in a Rugby Union scrum (Figure 1). A scrummage is an act in rugby to restart the game after a stoppage in play (Figure 3). Eight players of one team bind together in a 3-4-1 ‘pack’ formation against an opposition of eight players in the same arrangement, in attempt to push and win the ball that is fed between them. A single player can weight up to 120 kg (Paper 3, Section 1) and a combined pack weight can be up to 950 kg generating forces of 16.5 KN from impact between the two scrum packs (Preatoni *et al.*, 2013). The great magnitude of forces created and the documeted pitch failures (Section 1.1) provides indication of the stresses the the sports turf can be subjected to in failure.

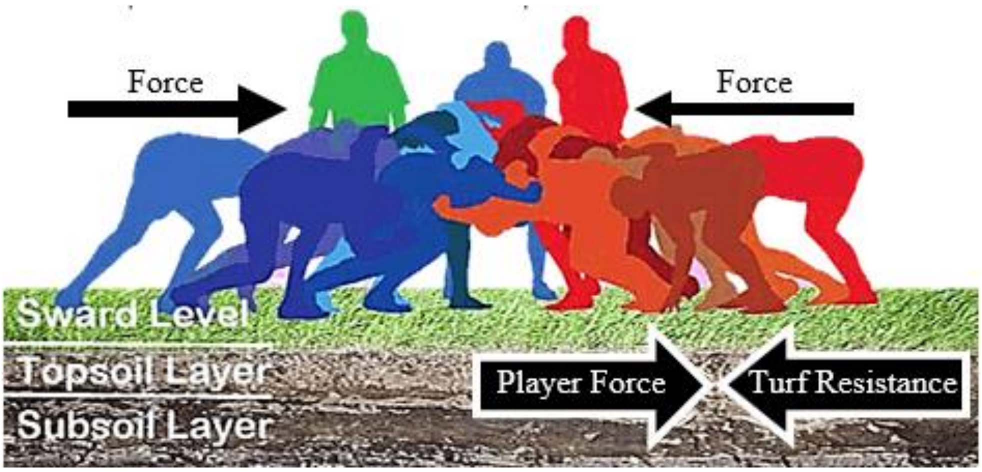


Figure 3 – Shear stability during a rugby scrummage

However, similarly to the hybrid turf, there is no readily availible research on scrummage foot force interaction on natural and hybrid turf. This lack of knowledge of the shear stability, the complexity of sports turf and the influencing variable (root density, soil water content, dry density) have made it hard to define the true cause of the shear instability in all cases. Unpredictability of the shear stability on the surface and to depth has presented a problem for groundskeepers and agronomists alike who do not have a method to predict this common failure.

1.2.3 CURRENT SPORTS TURF PITCH QUALITY ASSESSMENT

The PQS Framework (The Institute of Groundsmanship, 2001) became prevalent in the mid-1980s producing natural turfgrass standards to provide minimum quality indicators and aiding surface maintenance (Caple, James and Bartlett, 2012a). In addition to standardised agronomic tests, this saw the development and adoption of a suite of surface performance tests to measure surface characteristics (hardness, rebound, traction). The equipment developed attempted to replicate player and ball interaction on the surface, producing scalar results that determined quality with the benchmarked PQS range. The framework was later used to create a standard for many governing bodies. The most notable was The Fédération Internationale de Football Association (FIFA) 'Quality Program for Sportsturf' which assessed artificial turf, but could also be applied to natural sports surfaces (FIFA, 2006, 2015). The FIFA standard has been used by other sports governing bodies to develop their own standards.

The device used to measure the surface shear resistance in the PQS and FIFA was the RTD. At present, this is the only industry standard used by the governing bodies. This device measures the peak resistance when the turf surface 'fails' (FIFA, 2006). This has seen little alteration since the first conception of the standard; this also applies to the device's limits for 'good quality' that were established for the PQS in the 1980s. As suggested, sports turfgrass constructions have advanced and there are doubts the device still measures the correct ranges (Stiles *et al.*, 2009; Caple, James and Bartlett, 2012a) and its relatability as there are larger differences biomechanically to a player's performance on the turf (Damm, Stiles and Dixon, 2015). The test standard length (13 mm) of football studs used (also specified for rugby), means the result are mostly influenced by the grass leaf and near surface rootzone and cannot measure the deeper rootzone failure suggested in Section 1.2.2. Therefore, turf study and industry would benefit from a device that creates greater understanding of this deeper shear stability failure in the rootzone and research of non-standardised devices applied to turfgrass is required to offer assessment of shear stability of turf.

1.3 THE INDUSTRIAL SPONSOR

Labosport International are a group of independent testing laboratories specifically dedicated to accrediting sports surfaces and equipment. Labosport established in France 1993, and has since created branches in Europe (UK, Italy and Germany), Asia, Africa, Australasia and the Americas as a result of the increase in the technical sport surfaces market.

Labosport UK Ltd. have seen large growth in business in the last five years and expanded into other testing avenues. Labosport turnover in 2017 was around £3.1 million, this is an increase from £2.7 m in 2016 and £1.2 m generated in 2012. In addition to artificial sports surfaces testing and consultancy, Labosport also calibrate goal-line technology systems, sports pitch construction framework (key stage inspections) and in 2014 added agronomy specialists, Professional Sportsturf Design Ltd. to the Labosport group roster.

The EngD process benefited from Labosport's large job portfolio and in the first two years technical skills were developed from involvement in consultancy projects and writing standards for institutions and governing bodies (Appendix A and B).

1.3.1 LABOSPORT SCOREPLAY™

Labosports' acquisition of Professional Sportsturf Design Ltd. signalled a move to assess performance quality of natural and hybrid sports pitches by developing the Scoreplay™. The test was created to better assess natural and hybrid sports turf than the PQS, offering a percentile quality rating (poor to excellent) opposed to the minimum benchmark. This combined a suite of standardised agronomic test equipment with sports surface performance test equipment used for the FIFA standard. Each piece of test equipment was benchmarked with a large data set from trial tests of modern sports pitch assessments providing a quality rating score from poor to excellent for each (Figure 4). The individual scores were totalled together with an algorithm to create an overall percentage quality rating and a report was generated to help the client (groundskeeper) understand the data and improve the surface if required.

Since its conception Scoreplay™ has been used for more than 400 projects including: monthly visits to Wembley Stadium; repeat testing of English Premier League stadia and training grounds; repeat testing ahead of the Japan Rugby World Cup (RWC) 2019, and *ad hoc* testing worldwide.

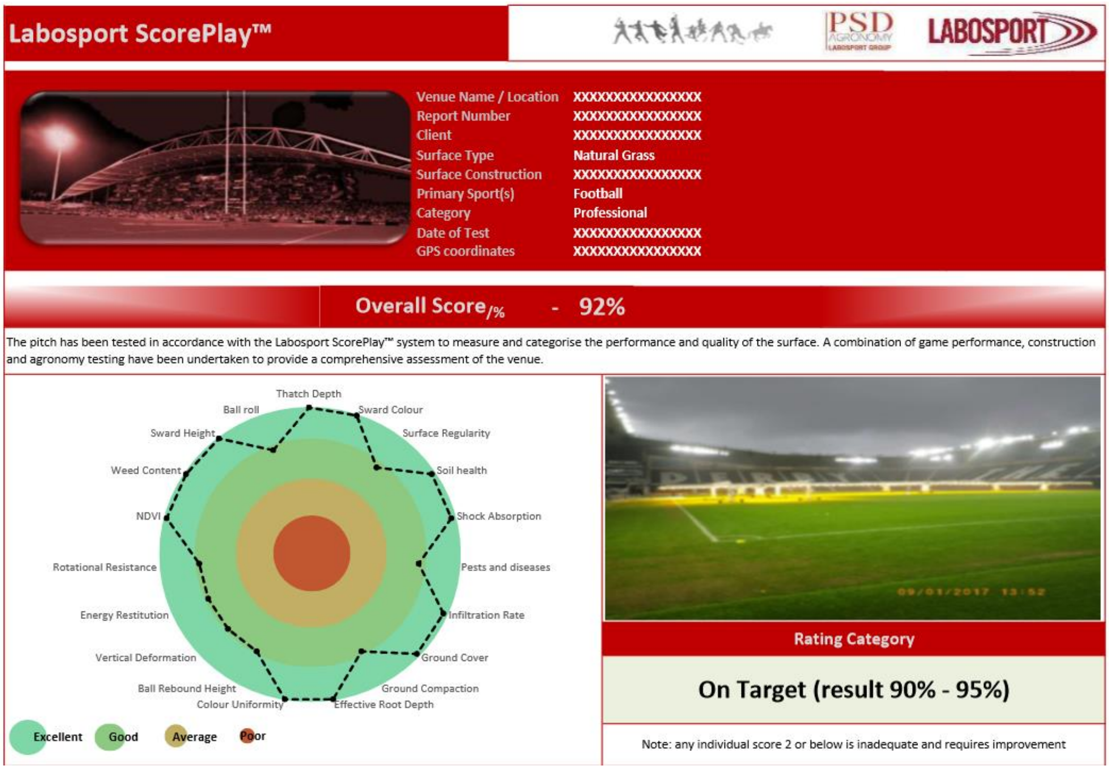


Figure 4 – An example of the Scoreplay™ result sheet showing the individual rating of each variable measured on a scale from poor to excellent and the resulting turf quality percentage

Although Scoreplay™ has been adapted to meets the need to assess the common sports construction more so than the PQS identified previously, it still had shortfalls as there was no assessment of the shear stability (as RTD only assessing near surface failure). Labosport market research indicated that there was no commercially available assessment method for natural turf surfaces' shear stability; there was in fact no market. This identified an area of interest for Labosport which would look to investigate this principle of shear stability. The best method proposed was to create a bespoke device that assessed commonly seen shear stability failures, providing the Scoreplay™ with a more complete assessment of pitch quality. The creation of the test was pivotal to Labosport as they won the contract to monitor and maintain stadium or training venues used for the England RWC 2015 (except St James Park, Newcastle-upon-Tyne).

As suggested previously, rugby scrummages were an issue for shear stability and a large number of venues were converted football fields, which more commonly experience smaller surface-player force interactions. Therefore, the priority was to accurately assess shear stability to ensure that the venues were of the upmost Scoreplay™ quality rating, preventing media and player backlash and raising the Scoreplay™ market status.

1.4 AIMS AND OBJECTIVES

The aims and the objectives were designed to meet the needs provided by Labosport and literature. This saw assessment of shear stability of sports turf to depth into the rootzone (100 mm). Elite-level pitches commonly experience failure under load by players and the current standardised device does not measure the turf resistance to these forces in the rootzone. Investigating this issue and providing a suitable test method is of interest to Labosport UK Ltd in order to provide better assessment of overall quality of natural and hybrid sports surface constructions.

1.4.1 AIM

Design and develop a field mechanical device to assess the shear stability of natural and hybrid turfgrass constructions

1.4.2 OBJECTIVES

1. Explore literature to define the variables that can affect shear stability of natural and hybrid turfgrass constructions under player loading

2. Evaluate the strengths and weaknesses of the current portfolio of standard test methods and relatable equipment used to assess aspects of turf and/or soil rootzone strength

3. Design and fabricate a device to measure the shear stability behaviour of natural and hybrid turfgrass sports constructions

4. Investigate the key variables that can affect the shear stability of natural and hybrid turfgrass constructions and benchmark the device measurements.
5. Develop a standard testing and analysis methodology to evaluate in-service sports fields
6. Disseminate the findings into academic and industry networks

1.5 NOVELTY OF THE RESEARCH

Shear stability of sports turfgrass surfaces was found to be a recurring problem at the elite level with its cause not fully understood. This failure is found to affect sports turf to depth into the rootzone, as detailed by agronomists but has little research evidence to support these claims. Furthermore, this shear stability currently has no standardised or commercial sports surface tests shown to measure or predict this form of turf failure. Therefore, the novelty is in development of a device that can effectively measure this shear stability and determines the variables that can influence shear stability for both natural and hybrid turf constructions.

1.6 STRUCTURE OF THE THESIS

The thesis structure is detailed in Figure 5, showing the project objectives and their associated research areas. Investigation into these research areas created the work packages that provide information to meet the project aim through the thesis sections and consequential outputs. Further details of the sections and outputs follow.

Section 2, Methodology: Introduction to the test methodology and techniques. Further information is found in discussion of the work packages and how they meet the objectives of the study. Considerations covered issues that were required to meet the study needs and work packages constraints were described.

Section 3, Research Literature: Detailed past literature and studies on turfgrasses' and soil rootzones' shear stability/strength variables; evaluation of related shear/surface performance equipment to meet objectives 1 and 2.

Section 4, Research Undertaken: A progressive design and development technique was used to produce the prototype device. This device was validated (laboratory study) and tested to measure shear stability variables of turfgrass constructions meeting objectives 3 and 4.

Section 5, Conclusions: The findings were compared with previous relatable literature to support the investigation of shear stability and evaluation of the effective variables, achieving objective 5. The implications of the findings to Labosport and the wider industry were then discussed (objective 6) and the future steps for the research were detailed.

Outputs were deliverables created from the findings of the work packages. These were three publications and incarnations of the prototype device, known as the 'Shear Tester' Mark I (MK I), Mark II (MK II) and Hand Pull (HP) devices. Figure 5 box colours indicate the research approaches used (detailed in Section 2 Methodology): green is qualitative, blue is quantitative, and purple is mixed methods.

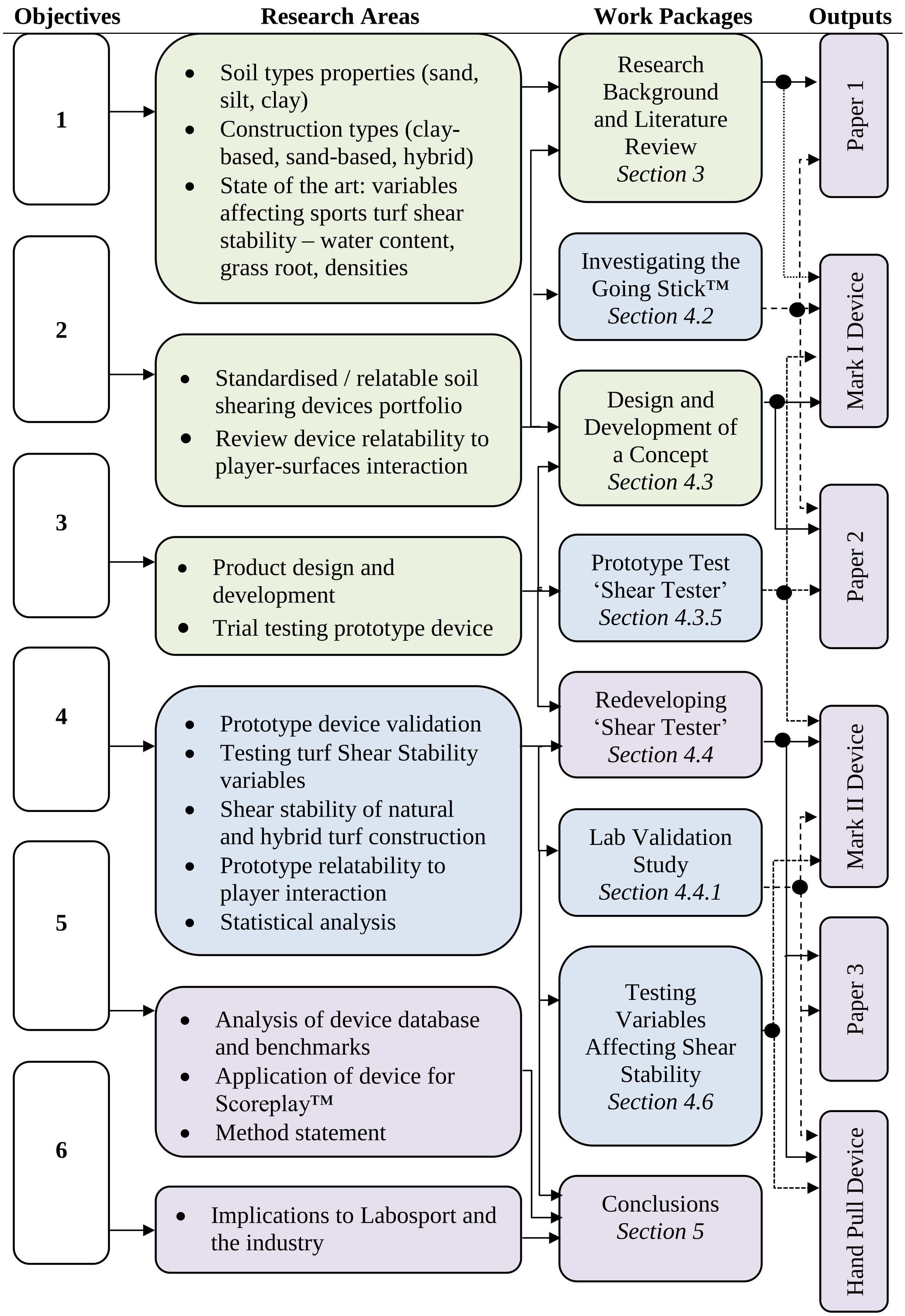


Figure 5 – Thesis Structure

2 METHODOLOGY

2.1 INTRODUCTION

The research methods and techniques chosen to meet the project's objectives are presented. The methodology was developed with reference to the widely accepted research engineering concepts published by Fellows and Liu (2009). Methodology considerations relative to the research objectives are first presented in a research map with reasoning and context of their subsequent development. Further detail acknowledges the constraints while conducting the study.

2.2 OVERVIEW

The research method refers to the manner in which the research project was undertaken, and research technique refers to the specific investigation tool by which the work is undertaken.

The research methodologies adopted have been separated to quantitative, qualitative and mixed research methods. Quantitative research is objective in nature, defined as an enquiry based upon testing a hypothesis, while qualitative research is subjective in nature, with an emphasis on experiences and description. Mixed method encompasses aspects of both these research methods, analysing numerical and narrative data.

Scientific research techniques tend to be quantitative, as they focus on the conception, design and creation (prototyping). Nevertheless, for all techniques the design of the research methodology is based upon a body of theory and topic knowledge. The output is subjected to rigorous testing and validation, to determine the extent to which the project aim is achieved. The research questions take the form of describing the how and why, with a high level of control required over variables.

Qualitative methods and techniques were developed within the research field of the social sciences. Grouping research techniques, included collecting case studies, past studies and statistically modelling. This form of the research question is dependent on the research technique employed, ranging between the how and why, and what measure for both. In addition, control over all variables is generally absent.

2.3 METHODOLOGICAL CONSIDERATIONS

The research methods were chosen by breaking down the research project into a series of research work packages and tasks associated with the objectives (Section 1.4), allowing selection of appropriate research methods and techniques. A summary of the research objectives, associated questions (research work packages), adopted methodologies and the subsequent outputs are presented in Figure 6. Box colours show qualitative (green), quantitative (blue) and mixed methods (purple) research methods.

Explanation of Figure 6 details project progression to meet the objectives by undertaking the related research work packages and methodologies. The work package tasks explore areas to answer the questions asked by the objectives, subsequently developing an effective method (discussed further in section 2.3.1–2.3.3). The three methodologies included gathering and reviewing subject literature, prototype development and experimental research. The outputs from the methodology describes the research papers and presents the findings.

Experimental research was used to meet all the objectives throughout the study. It was first used to produce Paper 1, which explored the industry shear strength devices best suited for application to natural sports turf. This was undertaken to improve the literature as there were only a few studies that utilised devices for shear strength and did not evaluated their advantages and disadvantages. The Paper showed some of the device’s features that could be included and informed the prototype ideas, although they were found to be lacking certain features themselves (meeting objectives 1 and 2) (Paper 1, Section 4). The experimental research was combined with development of the prototype in a mixed method to trial the ‘Shear Tester’ device (Paper 2). This explored the functionality of the device in predicting shear stability and informed further development (objective 3). Paper 3 redesigned and validated the Shear Tester device in a laboratory study controlling the rootzone variables to provide results in line with widely reported fact. It also established understanding of the devices' test mechanism, applying a conceptual model to the device. Further experimental work increased understanding of the device's mechanisms to the changes in turfgrass variables (objective 4). Progressive redesign of the Shear Tester saw improvements in the data collection and experimental methods exploring soil confinement, applying it to the conceptual model. Comparison between the iterations of the Shear Tester devices were used to investigate similar functionality.

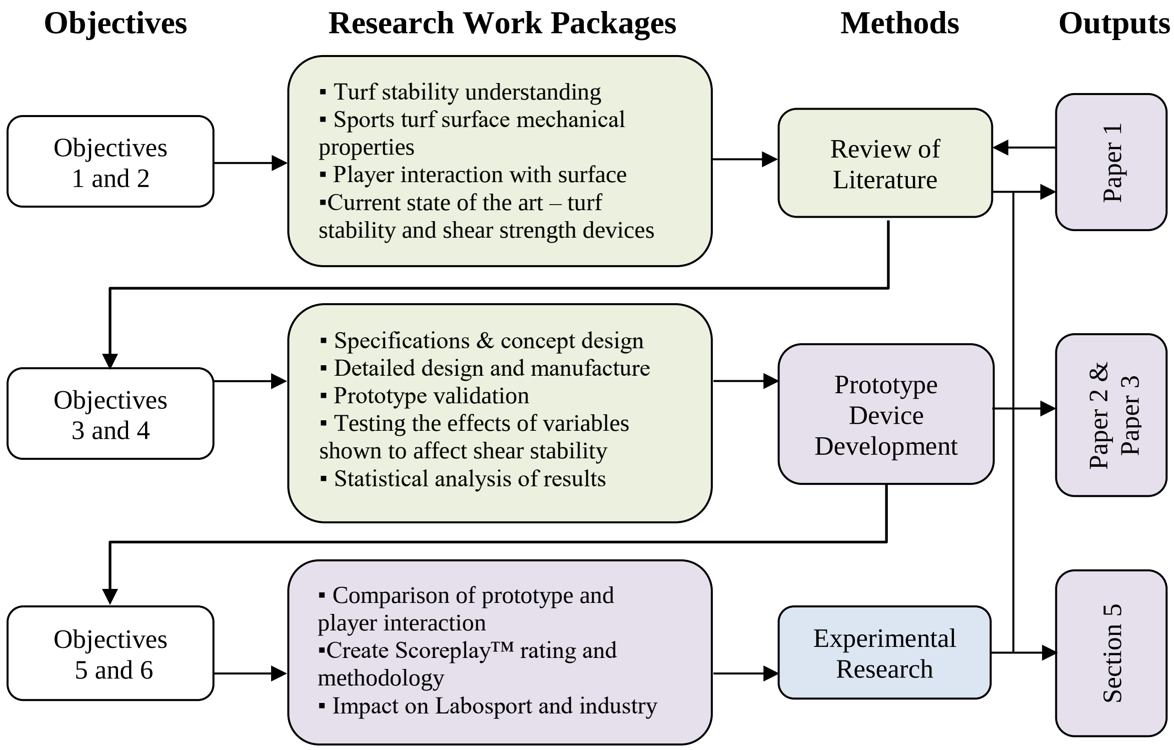


Figure 6 – Flowchart detailing the project objectives, work packages, methods and outputs. research methods show: green for qualitative, blue for quantitative and purple for mixed methods

The experimental research laboratory study tested bare soils. Therefore, to evaluate the shear stability variables a turf farm plot study was initiated to measure differences in root growth and plot construction. There were concerns about the low soil densities reported throughout this study, thus opportunist *in-situ* testing was undertaken on a sizable number of active sports pitches. To enhance the findings a final independent study for water content, (a key variable of shear stability) using a clayey *in-situ* pitch was undertaken. Statistical methods were then used to show clearly the variable relationships both to each other and to their contributed effect on shear stability.

The large data set collected provided greater understanding of the device and the variables that affect shear stability, propagating information to produce a Shear Tester standard method (objectives 5) and project impact and conclusions (objectives 6) in Section 5.

2.3.1 REVIEW OF LITERATURE

The review of literature meets the needs of objectives 1 and 2, establishing foundations of the project. Paper 1 and the literature are mixed and qualitative methods, respectively, and interlink, providing useful outcomes in understanding the current state of knowledge and driving the need for design development. The outcomes from the literature search were:

- Gaining knowledge of the sports turf constructions and the related surface industry and evaluating the extent of the shear stability problem in the sports surface industry from past projects.
- Evaluating relatable methods that are/could be used for testing sports turf surfaces shear stability. This includes its relatability to the turf/player interaction on the surface and its suitability for *in-situ* field use.
- Reviewing the equipment used for standardised assessment of the surface mechanical properties.
- Reviewing studies from papers that explored the variables that affect shear stability.

Challenges in providing literature stem from the lack of understanding of the shear stability and appropriate test methods stated throughout the introduction and the lack of a method to assess the deeper shear stability failure (Section 1). There were also challenges in predicting rugby player's foot interaction and forces as available literature looked at force impacts of players shoulders as opposed to foot interaction forces with the surface, which was not defined (detailed in Section 3.8.2). Therefore, most of the information was adapted from related studies providing indication of the potential causes for the shear stability.

2.3.2 PROTOTYPE DEVICE DEVELOPMENT

The development of the device was undertaken with reference to the scientific research technique Total Design (Pugh, 1991). This saw research associated with specifications, conceptual design, manufacturing and development, including experimentation with test equipment, software and protocol development (meeting objective 3). Evaluation of the market is not discussed further as this was detailed in Section 1.3.1 (Labosport's Scoreplay™). Each stage of development was evaluated and, where required, amended, producing a refining process. The prototype development process was initially focused on designing, developing and trialling equipment and procedures, before moving onto device validation and further shear stability characterisation of the experimental research (objective 4). Challenges were created when designing the prototype as the device was distinctly different and, owing to the complexity of turfgrass construction, the literature in most cases had to be manipulated to produce calculations for the design features. The prototype theory could only be understood fully with trial experimentation and, as stated, could be amended. Key research methodology considerations included defining the test specifications, developing a clear design brief, and managing design alterations.

2.3.3 EXPERIMENTAL RESEARCH

In order to create a sound device methodology (objective 5) and produce precise results, there needed to be rigorous experimentation planning to produce outcomes and offer improved project impact findings to meet objective 6. In order to develop and assess the practical use of the prototype, the following factors required consideration and evaluation during the experimental research:

- Repeatability – Each test per experiment undertaken must follow the same data collection method to achieve meaningful results. This means that operator interaction must be the same each time the equipment is used.
- Reproducibility – During each experimental period the same method must be applied so that the details from all the experiments conducted within that period have been collected in the same way.
- Consistency – Where appropriate, the factors that are not measured need to remain constant during each experimentation and between each test.
- Measurement – Where calculations are used, accurate assessment of the properties are required to produce exact, meaningful results as poor data collection could produce outliers.

2.3.3.1 Experimental Research Studies

Most of the experimental research was scientific experimentation, with only one using a statistical method. These are detailed in Table 3 stating the objectives they met through their undertaking.

Table 3 – List of project objectives met by undertaking the different studies

	Experimental Study		
Objective 1 and 2	▪ Trialling Related Shear Devices		
Objective 3	▪ Prototype Trial	▪ Laboratory Testing	
Objective 4	▪ Laboratory Testing	▪ Grass Plant Establishment	▪ Soil Water Content
Objective 5 and 6	▪ *In-situ* Testing	▪ Statistical Analysis	

The experimental studies provide development in knowledge that progressed the project meeting further objectives. Each study is described in more detail below.

Trialling Related Shear Devices (Paper 1) – This initial study investigated the available shear strength test methods to find if they could be applied to measuring the shear stability of sports turf constructions. Consideration of methods required them to be portable with simple, fast assessment methods.

Prototype Trial Study (Paper 2) – A prototype, the MK I Shear Tester device, was manufactured and underwent a trial study during the RWC testing. The main objective was to trial the device and determine whether it could successfully show variation in shear stability of a variety of pitch constructions. Prototype testing was accompanied by the Scoreplay™ test. This offered evaluation of some of the best quality pitches available and the Scoreplay™ data sets could be compared and benchmarked to the prototype result.

Laboratory Testing (Paper 3 and Appendix F) – The laboratory testing was used to validate the newly manufactured Shear Tester MK II and evaluate the different device design features. The main objective was to investigate the results produced by the devices using different water content, soil textures, density and confinement levels. The same method was used to evaluate a further design – the HP Shear Tester.

Grass Plant Establishment Study (Appendix G) – This study investigated the dependency of shear stability on the effect of grass plant establishment in various plot constructions. The study tested six different natural and hybrid constructions plots with the MK II Shear Tester device over a 16-month period as perennial ryegrass was grown and matured into them. Soil/agronomic tests were used, and environmental conditions were continually monitored.

In-Situ Testing – This study was used to test and monitor the shear stability of active *in-situ* natural and hybrid sports turf. The tests were undertaken during commercial Scoreplay™ and other *ad-hoc* visits (86 in total). In addition to Shear Tester and Scoreplay™ results, core collection (see Section 3.6.3) was also undertaken when possible. These were combined to create sizeable data set of results that could be applied to developing the device methodology.

Soil Water Content Study (Appendix H) – The study investigated the effects of water content on shear stability in a sandy clay loam (See Section 3.2.2) soil football pitch that was first water saturated and then left to dry out over a week. Tests were conducted each day to monitor changes in shear stability. The purpose of the study was to find the shear stability behaviour of an *in-situ* clay-based turf construction across a range of water content conditions.

Statistical Analysis (Appendix I) - In order to understand the trends and relationships between variables and the shear stability results the data collected from all the studies was analysed with IBM® SPSS® 23 Statistics Data Editor. The array of variables was compared singularly with each other by bivariate correlation using two-tailed Pearson's correlation to offer insight into relationships between variables. As many variables are interacting in the turf at the same time, shear stability was compared with multiple variable relationships using linear regression models to provide indications of the combined percentage dependency the variable had on the result.

2.4 CONSTRAINTS OF THE STUDY

The Introduction (Section 1.2.1) highlighted that there are many variables in the turfgrass system that can constantly interchange. This complexity makes it difficult to control all the variables (rootzone texture/construction, water content, grass rooting and density) in experimentation: These factors were more easily controlled in laboratory experimentation. As there was less control in the field and recording all the variables was therefore vital in order to determine their influence on shear stability at depth, if any.

Collecting turf cores was undertaken when possible. The core collection provided useful information for grass root growth, bulk and dry density, voids and the gravimetric water content measure (all discussed in Section 3). However, owing to contractual constraints in the RWC study, cores could not be collected. In order to measure water content, a time domain reflectometry (TDR) probe was used. This measured volumetric water content, which has been shown to more variable than the gravimetric water content (Fernández-Gávez, 2008). This exclusion of results meant the RWC study did not provide the same degree of detail of rootzones as the other studies, removing the ability to fully compare its findings.

2.5 SUMMARY

The methodology introduces the methods and techniques used to achieve the aim and objectives of the EngD project. The use of qualitative, quantitative and mixed research are strong themes throughout the study and are developed into three research methods to advance the project and meet all the objectives.

Gathering qualitative information on the subject built understanding of the shear instability of sports turf and the associated and standardised test devices (Section 3). This in turn produced qualitative design of the prototype, which was trialled, redeveloped and validated using a mixed method (Section 4). The confidence in the redeveloped prototype provided rigour to explore variables affecting turfgrass shear stability and statistical models could provide relationships to the variables despite them constantly interchanging (Section 4.6). Meeting these methods then provided the basis for discussion of the results comparatively with the literature, the impacts of the study and a precise, designed device test method (Section 5).

3 REVIEW OF THE LITERATURE

3.1 INTRODUCTION

This section introduces the literature surrounding shear stability of natural and hybrid sports turf. The sports turf analysis discusses the turfgrass variables in greater detail than the background introduction.

To meet objective 1, the variables included in the turfgrass are examined initially providing an understanding of the variables (construction types, the soil texture and the grass plant) and specifying literature relevant to shear stability from past research on the topics.

Objective 2 was met by discussing tests used for the assessment of natural sports turf constructions and relatable available equipment to measure shear stability/strength. The test equipment was detailed and evaluated using past literature to identify the equipment's qualities and shortfalls. Relatable shear strength tests were chosen based on their potential in being applicable to assess natural sports turf for the project aim, namely shear stability of turf/rootzone to depth. To provide equipment relatability to player interaction, a literature review of the scrum forces was produced. Player foot forces running on natural turf was also detailed as there was limited information provided on scrum foot/surface interaction (as stated in Section 1.2.2).

3.2 NATURAL AND HYBRID TURFGRASS CONSTRUCTION

The construction profile of natural and hybrid turf can have many variations described in British Standards Institution (2007a); Sport England (2011); and James (2015) (Figure 7). The turf's construction commonly has a grass leaf surface which is usually cut to a height of 20–25 mm for football and 35–50 mm for rugby. The grass is grown into a soil rootzone, which is a controlled growing medium. The rootzone composition can vary widely depending on the proposed use of the sports turf containing different soil textures (see Section 3.2.1) or hybrid components (Section 3.2.3). For many general-use sports venues the rootzone typically comprises a surface top-dressed with sand with the clay subsoil material underneath. Elite-level sports venues typically have a 200–300 mm deep rootzone layer of a sand-clay mix at a ratio of up to 90:10 by mass (James, 2015). To aid rapid drainage of surface water a porous sand/gravel layer is often included below the rootzone and above the *in-situ* subsoil, and a further pipe drainage network in the subsoil may also be required (James, 2015). Turf is either grown *in-situ* onto a fully prepared natural or hybrid rootzone or, alternatively, a turf system grown at a specialist supplier is imported and laid onto a prepared base. For this method the imported turf sections are usually 50–80 mm thick, 2 m wide and up to 25 m long.

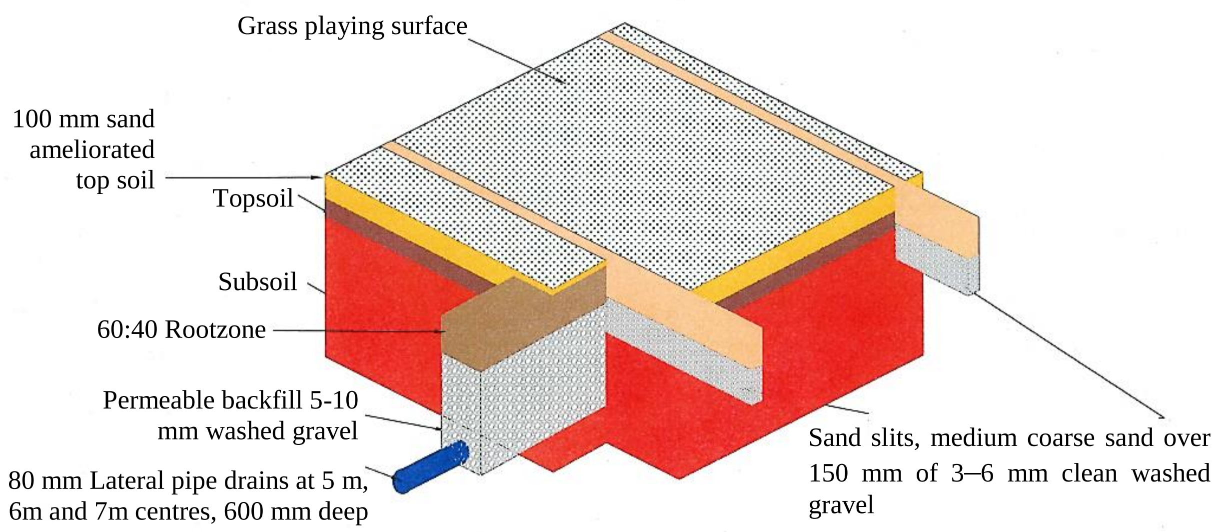
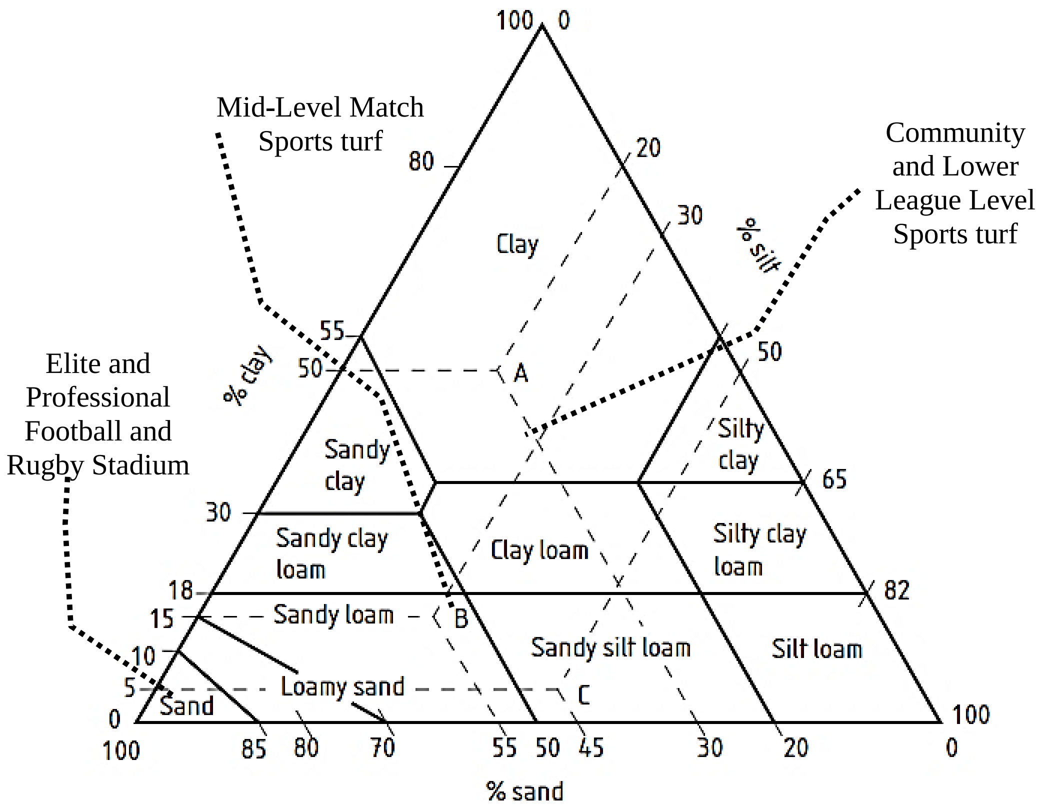


Figure 7 – Cross-section of common sports turf construction

3.2.1 ROOTZONE SOIL TEXTURE

The soil texture can influence the characteristics and behaviour of the turf pitch. The rootzone materials are separated between ratios of the three soil textures: clay, silt and sand.

Figure 8 shows a soil texture characterisation chart used to determine the soil texture percentage. Adapted from James (2015), the percentiles readily used for the different performance levels are indicated, although, realistically, pitches can be anywhere in the percentage scale of the triangle. A common community level pitch generally has a higher percentage of clay (clay-based). A mid-level pitch construction can range from clay loam to a loamy sand. The sand-based constructions (up to 90 % sand) are reserved for the elite venues (James, 2015). This is due to the continual and costly maintenance of the sports turf but with the attribute of effective drainage (see section 1.2.3). The soil mechanics can vary based on the characteristics of each soil texture and their percentile inclusion, therefore, there is importance in defining soil texture percentage by testing particle size distribution (PSD) (British Standards Institution, 1990b).



NOTE Examples of textural classification:

Soil A with 30% sand, 20% silt and 50% clay is in the "clay" textural class;

Soil B with 55% sand, 30% silt and 15% clay is in the "sandy loam" textural class;

Soil C with 45% sand, 50% silt and 5% clay is in the "sandy silt loam" textural class.

Figure 8 – Soils percentile identification chart (British Standards Institution, 2007a) indicating, with reference to James (2015), the common associated performance levels of a sportsturf field

Soil texture density (bulk and dry) indicates the compaction that can affect the mechanical properties, void ratio and turfgrass health (Arshad, Lowery and Grossman, 1996). Dry density is a measure of compaction for dry soil and bulk density measures wet soil and its water content. Dry density is the more suitable measure for the soil's suitability for plant rooting.

No studies have detailed ideal conditions for sports turfgrass, however, agriculture has widely reported the ideal and restrictive conditions for plant growth (Table 4). The table also states a range of typical dry density (Mckenzie, Coughlan and Cresswell, 2002).

Table 4 – Dry density ranges adapted from Arshad, Lowery and Grossman (1996) and Mckenzie, Coughlan and Cresswell (2002)

Soil Texture	Typical Dry Density Range (g/cm^3)	Ideal Dry Density for Plant Growth (g/cm^3)	Bulk Densities that Restrict Root Growth (g/cm^3)
Sandy	1.3–1.7	1.6	1.8
Silty	1.1–1.6	1.4	1.65
Clayey	1.1–1.6	1.1	1.47

Pore space (void ratio) is another characteristic that can indicate conditions for ideal root growth. The soils pore space is defined by the space not occupied by particles in a bulk density volume – containing a percentage of air and water. Pore space can vary from 35 to 70 % of the total soil volume depending on the soil bulk density and optimal pore space for grass growth under trafficked conditions is 35–40 % (Beard, 1973). Ideally, the pores space will have an air void ratio between 15 % and 30 % for effective plant growth, although the air voids can decrease to 10 % with minimal impact on the grass plant. Adverse effects appear below 5 % air voids (Thomas, 2000), where near-saturating levels of water content create conditions high above the soils field capacity, with little to no oxygen and the turf plant becomes stressed (James, 2015). Field capacity is the amount of water content held in the soils after excess water is drained away and the rate of movement has decreased.

Adverse effects can also be seen in soil when water content is at a low level and the grass can no longer remove water from the soil because it is being held too tightly. This is known as the permanent wilting point (Saxton and Rawls, 2006). Table 5 details the different volumetric water contents for field capacity and wilting point for the soil textures.

Table 5 – Field capacity and wilting point adapted from Saxton and Rawls (2006)

Soil Texture	Field Capacity (Vol %)	Permanent Wilting Point (Vol %)
Sand	10	5
Silt	28	14
Clay	42	30

The density, pore space and water content can affect the shear strength of the soil textures. Figure 9 shows a stress strain curve from Barnes (2010). When the sand or clay is low density and clay has a high water content (soft) then the shear stress is less and as strain increases at a gradual rate to the ultimate stress (U) where it levels off where it reaches the critical state strength (C). If the sand is confined and/or clay is compacted (with low water content), then the stress increases to a greater level with lesser difference strain until it reaches a peak strength (P) and decreases. This peak in strength is caused by the particles interaction as they which are closely packed under greater density and lock together more so than in loose soils. More energy is required to move the particles and so they resist shear until enough energy is present for the particles to slide over each other, indicated by the peak strength (P). After this point the particles loose resistance and move more freely reducing the shear strength with further strain.

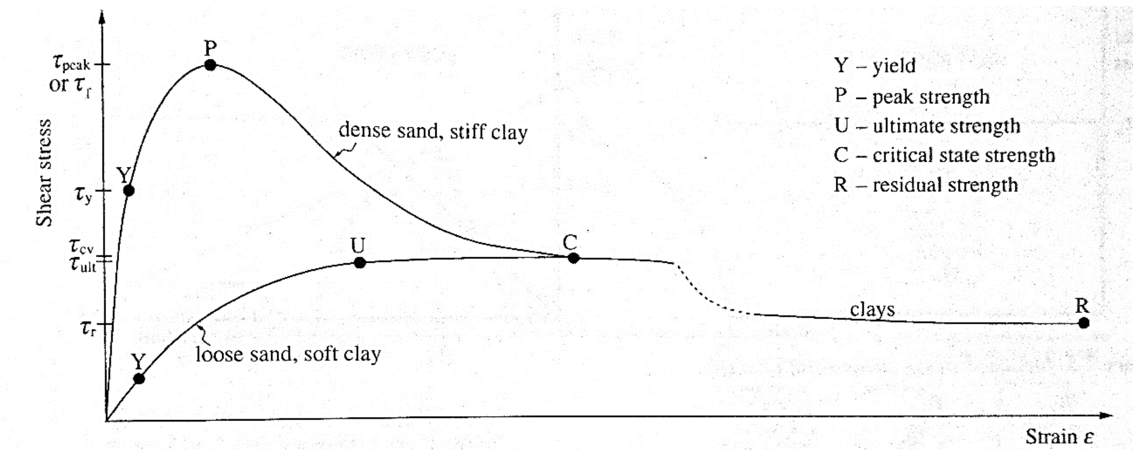


Figure 9 – Diagram (Barnes, 2010) showing changes in the stress/strain behaviour of clay and sand for differing densities

This section detailed the material's textures and the effects of density, porosity and permeability on grass rooting and shear strength. These factors all contribute to the shear results and so sometimes it can be difficult to define the exact cause for shear values obtained.

3.2.2 NATURAL TURF CONSTRUCTIONS

3.2.2.1 Clay-Based Sports Turf

Clay-based sports pitches can be referred to as 'native' as they are commonly the *in-situ* soil. Clay particles, mainly alumina-silicate, are small in size (< 2 μm), have many small pores with a high surface area and are chemically reactive (Arthur, 1997). This proximity causes bonds from electrostatic forces (Van der Walls) holding onto water in tension through air suction. High cation exchange capacity means clays hold essential nutrients readily (Beard, 1973; Arthur, 1997). When in the correct balance, clays exhibit superior conditions for plant growth and display 'cohesive' properties, whereby they can maintain shear strength independent of external loading (Barnes, 2010).

However, clay-based systems possess low permeability and poor drainage capacity, making them sensitive to water content. Therefore, as the water content in the clay soil increases , bonds between clay particles weaken, reducing the shear strength and leading to greater plastic deformation under load (Barnes, 2010). The small structural particle size also means that clays are liable to compaction, generating stress in root formation and preventing aeration (Arthur, 1997).

Clay also experiences shrink–swell behaviour with change in water content, whereby particles undergo reorientation owing to the change in surface tension forces (Mumford, 2006). Water can penetrate between adjacent clay minerals hydrating substituted cations. The changes in water content creates an inter-particle binding strength with small pore size distributions creating low hydraulic conductivity and at times not allowing water to the roots (Guisasola, 2008). When dry, this soil reorientation causes the surface to increase in density and the surface becomes hard (Caple, 2011).

3.2.2.2 Sand-Based Sports Turf Construction

Sand-based constructions are used primarily for their effective drainage capacity. Sand-based systems commonly need to be transported and constructed on site (James, 2011; Sport England, 2011). Sands are hard brittle inert, mostly quartz, larger pored-sized particles (63–2000 µm) relative to clay (Beard, 1973), and therefore hard to saturate with water.

The inert properties and large pores mean nutrients readily leach through the soil away from the grass plant. Fertiliser and irrigation is regularly applied in order to maintain grass health (Stiles *et al.*, 2009). The inert sand particles also have issues with stability as only frictional force between each particle stops them from moving/slipping over each other, and they therefore require less energy to move. The effective drainage and low-energy frictional forces mean sand's shear strength is less sensitive to changes in water content properties than clays (Guisasola *et al.*, 2010). When sand is compressed, the frictional forces and angular flexion increase making the sand stronger (Guisasola *et al.*, 2009). Sand can also exhibit improved strength when 'apparent cohesion' occurs over a small range of water content, which forms a non-cohesive bridge (suction) between particles (Mumford, 2006; Guisasola *et al.*, 2009; Caple, 2011). The medium-sized sands are the most suitable for turfgrass construction, allowing the grass roots to grow into the spaces between the soil particles and offering the most effective drainage (Arthur, 1997). The particle shape is also important and the optimal shape for a particle is semi-rounded. This creates a soil that locks together, reducing the amount of available pore spaces (Guisasola *et al.*, 2009).

Sand qualities mean it can be readily mixed in the rootzone blend with peat, organic matter or clay to promote better plant health, retaining greater water-holding capacity and nutrients in the soil, while maintaining useful hydraulic characteristics (ASTM, 2010). Sand can also top-dress clay-based constructions to agglomerate the soil or create channels called sand drains, to offer a cheap measure for more effective drainage than clay-based turf alone.

Although not a pitch construction in its own right, silts are intermediate particles (size range 2–63 μm) present in both clay- and sand-based constructions. Their proportion in the soil textures influences the engineering and hydraulic behaviour of the rootzone and subsoil (James, 2015).

3.2.3 Types of Hybrid Construction

3.2.3.1 Reinforced Rootzone

Reinforced rootzone (Figure 10) have inclusions of synthetic additives. There is a large variety of additive products available (Serensits, McNitt and Petrunak, 2011; Hejduk, Baker and Spring, 2012). However, the most commonly used is a product called Fibresand™ that mixes long hydrophilic synthetic polypropylene (PP) fibres into a sandy top soil rootzone material before installation. The fibres are suggested to bind the sand together, forming an apparent cohesion to mimic that of clay in plant rooting (James, 2011). When grass is seeded and grown into the construction then the rooting is suggested to interact with the fibres to support them. This, in turn, increases the strength of the soil (James, 2014).

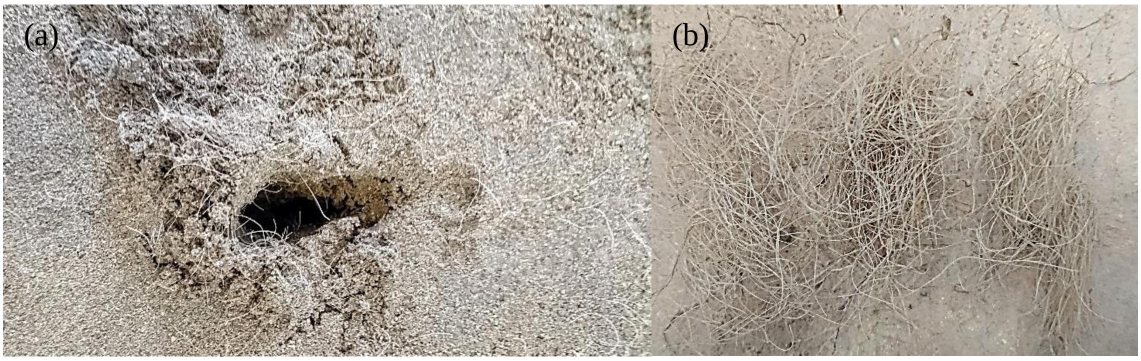


Figure 10 – (a) the PP fibres randomly orientated in the Fibresand™ rootzone: (b) shows a PP fibres bundle

3.2.3.2 Carpeted Hybrid Constructions

This geosynthetic turf (Figure 11) resembles a 3G artificial carpet. There are a large number of suppliers and products available for these constructions, but most have a biodegradable backing or netting with woven vertically standing green fibrillated plastic fibres of 30–50 mm length.

The carpeted/netted sportsturf is constructed by removing the topsoil and inserting a sand rootzone and carpet which is inserted to a depth of 30–50 mm. Grass is seeded into the soil and after the grass plant has matured, the carpet has been reported to provide a strong mesh just below the surface, interacting with the grass rooting and protecting grass leaf from excessive wear (James, 2011). If the carpet's grass coverage is reduced then the surface is less likely to divot than sand-based constructions (Sherratt, Street and Gardner, 2005).

Figure 11 – Examples of (a) backing and (b) woven netted hybrid systems

3.2.3.3 In-situ Injected Synthetic Construction

Injected synthetic fibre (Figure 12) constructions insert PP fibrillated fibres horizontally into the sandy soil to a depth of 200 mm (James, 2011). The fibres usually have 20 mm of material present above the surface. The fibres are injected into the rootzone across the pitch area every 20 mm by 20 mm square. It is claimed that the injected fibres act as a composite material, taking strain instead of the soil and holding it in place. The fibres create a path of least resistance for water, wicking it away from the surface, draining quicker than sand alone. When grass roots establish it is claimed that they bind to the synthetic fibres with the 20 mm of fibres present above the surface providing support for the grass stems (Desso Sports System, 2014).

Figure 12 – A core of injected synthetic fibre construction

3.3 SOIL AND TURF CONSTRUCTION RESEARCH

Research has shown that shear strength in clay soils improves as water content decreases (Tengbeh, 1993), whereas for sands, there is an increase in shear strength then a decrease as it dries further (Guisasola *et al.*, 2009). However, the rate of change in shear strength is dependent on soil texture and whether or not there are grass roots present. Shear strength in clay soil texture (see Figure 9) has been shown to increase by at least 1.7 times more than in sandy clay loam – using a Shear Vane (detailed in Section 3.6.1). In all soils, however, there are greater changes in strength with small changes at low water content than with high water content or near-saturation (Figure 13). This is due to the greater packing of molecules and adhesion (Tengbeh, 1993).

This was similarly demonstrated by Clarke & Carré (2017) when comparing water contents of the soil rootzone on traction resistance, relating to shear strength. Samples of turf were retrieved with a mixed soil rootzone (not defined) from a playing field. Water content was adjusted by drying back and wetting the samples, and then tested for peak traction resistance using a standardised RTD (detailed in section 3.6.1) measuring torque. The results demonstrated a strongly non-linear relationship, whereby when soils were too dry (circa 15 % gravimetric water content) percentage or too wet (circa 28 % gravimetric water content) around half the traction resistance was observed compared with a gravimetric water content of circa 23 %, suggesting an optimal value.

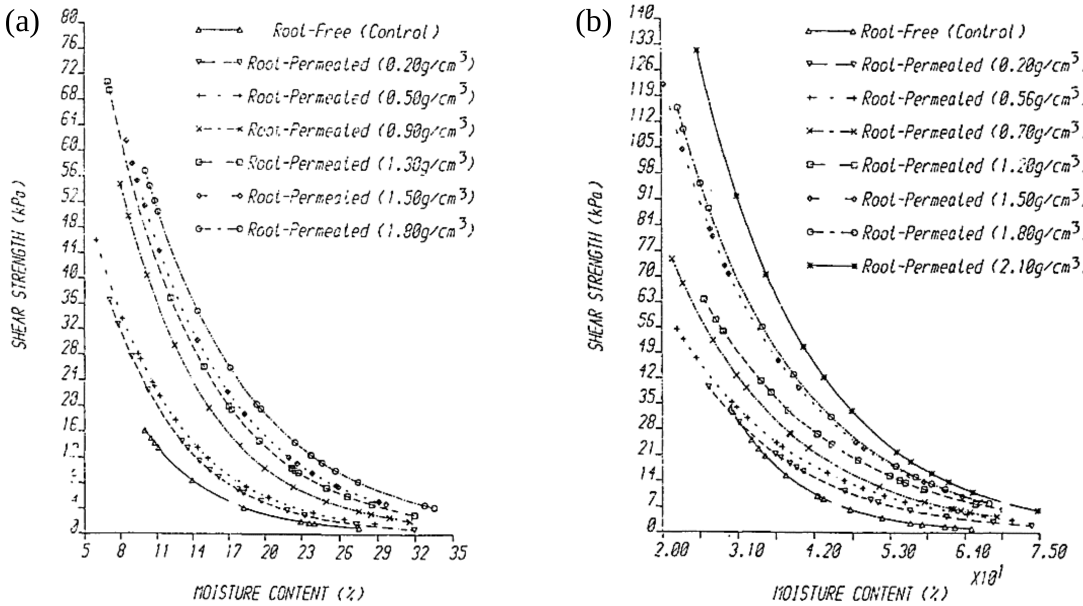


Figure 13 – Tengby (1993) diagrams of different root densities showing the difference in shear strength as water content (moisture) increases for (a) sandy clay loam and (b) clay soils

Density can be another factor influencing sports surface characteristics. It has been found that bulk density is related more to surface hardness than to water content. If a soil reduces in density then the resulting shear strength and elastic moduli are affected both in sandy and clayey samples because of reduced packing (Guisasola *et al.*, 2009; Hejduk, Baker and Spring, 2012).

Further information from Guisasola’s (2009) study using soils subjected to rapid undrained triaxial testing using a dynamic triaxial soil testing system (GDS DYNNTS 2 Hz 10 kN, GDS Instruments Ltd., Hampshire, UK), determined that strain softening was observed for some higher confining pressure. This was caused by dilation as densely packed particles moved upwards and over adjacent particles, causing brittle failure along a few well-defined failure planes. Treatments caused dilation and failure at a peak stress, and then ‘softening’ to a more constant ultimate stress (similar to the observations described in Section 3.2.1, Figure 9). When water content is constant, Poisson’s ratio and yield stress increase significantly with an increase in the initial dry density. This results in an increasing shearing resistance and cohesion from arranged, densely packed particles with increased particle–particle contact surface area. This links to Section 3.2.1 and presents evidence that shear strength of soils was dependent on dry density and water content, as readily seen in clay loam.

To reduce density, synthetics are introduced similar to that stated in Section 3.2.3.1. These hybrids also encourage water retention in high sand surfaces and provide shear strength. A number of studies mixed different materials into the rootzone to investigate these properties (McNitt and Landschoot, 2003; Serensits, McNitt and Petrunak, 2011; Hejduk, Baker and Spring, 2012).

McNitt & Landschoot (2003) and Serensits et al. (2011) undertook plot testing with different carpeted systems and materials additives incorporated into the rootzone. Plots were seeded with ryegrass and varying levels of artificial traffic were applied to the samples over time (McNitt and Landschoot, 2003). The shear strength was measured by a divot created by a ‘divot tester’ (detailed in Section 3.6.1). This was a pitching wedge golf club is attached to a pendulum and the greater the length of divot was equivalent to lower shear strength, and hardness was measured with the Clegg Impact Hammer (CIH) (detailed in Section 3.6.1). Findings showed that carpeted systems increased in hardness when greater wear was applied. However, this did not increase the bulk density of the soil and resulted from the increase in soil strength near the rootzone surface. Serensits *et al.* (2011) found that the stability decreased with higher traffic on different plots. This was seen to a lesser extent in the reinforced materials. However, at lower density (no traffic) stability was highest and the control plot (sand/peat mix) had similar results to the reinforced materials – theorised to be due to effective grass rooting that was unaffected by increased density from traffic.

Hejduk *et al.* (2012) undertook a laboratory study with different synthetic and natural additives. These distinct mixes had a high sand content soil in plastic cylinders to set depths – upper (less than 150 mm) and lower (150–300 mm). A known quantity of water was added and drained with soil water content taken throughout the study. The shear strength of the soils was measured with a Shear Vane (Section 3.6.1). This Shear Vane is inserted into the soil and the head is rotated building resistance until the soil fails. A mechanical gauge measures the shear strength of the device. The findings revealed that application of the additives to the lower level (greater than 150 mm) did not affect the upper water retention, with some synthetic and both the natural additives (peat and compost) increasing both water retention and shear strength.

3.4 TURF GRASSES

There are over 5000 species of grass with 600 genera, all carrying differing characteristics (Beard, 1973). Grasses can be subdivided into cool or warm season grasses. As many countries experience seasonal weather, many grasses are transitional, meaning they grow in both warm and cold climates. The EngD methodology was all undertaken in the UK, therefore, this study focuses on species commonly used in turfgrass in cooler climates, namely perennial ryegrass and meadow grass. Detailed description of the grasses properties are presented in Arthur, (1997) and Beard, (1973).

3.5 GRASS PLANT RESEARCH

There have been several relatable studies used to measure the influence of turfgrasses in sport turf or other areas. The important interactions of the turfgrass plant in the soil have suggested that the presence of turfgrass can increase the strength of soils by up to 325 % to 850 % (Shildrick and Peel, 1984; Tengbeh, 1993; Comino and Druetta, 2009), reduce the displacement of soil (Comino and Druetta, 2009; Caple, James and Bartlett, 2011) and increase soil cohesion in dry soils (De Baets *et al.* 2008).

Comino (2009) and Tengbeh (1993) both explored root shear strength on certain soils. Comino sought to measure the turfgrasses' influence on shear strength in alpine slip conditions. The three sites chosen were high sand content, *in-situ* alpine environments. The sites were tested 8 months after seeding multiple species and undertaking three trials. A shear box (300 x 300 x 100 mm) powered by a hydraulic jack with guide rails and a load cell was used to determine the shear force applied and the resulting displacement. The failure plane was to a depth of 100, 200 and 300 mm, and the grassed soil and controlled bare soil were tested under the same conditions. The highest resistance was 325 % and peak shear strength was 5.1 kPa. The study showed high variability in results caused by species differences. The variety in results at each location per species was due to many uncontrolled factors: particle-size compositions of the soils tested, chemical and physical characteristics, densities, water content and cohesion with the roots, the presence of voids and old or non-uniform distribution of roots (Morgan and Rickson, 2003; Normaniza, Faisal and Barakbah, 2008).

Tengbeh (1993) suggested that grass could increase soil strength by 850 % after undertaking a laboratory study using a sandy clay loam (500 % increase) and clay soil (850 %) from Bedfordshire, England. After being prepared in boxes (1 x 0.3 m), soils were seeded with perennial ryegrass to different concentrations, grown in a greenhouse and tested at intervals between 4 and 30 weeks. During sample collection, the soil was saturated with water. Stability of the soil and grass as it became established was determined using a hand Shear Vane and a core was taken to determine volumetric moisture content. The results indicated that turfgrass grown into the soil at all stages of growth gave higher strength than the soil samples with no grass. Grass root density held the water more strongly than soil alone and the roots were found to create better cohesion in the soil.

The displacement of soils from turfgrass is also widely researched. In Comino (2009), experimentation suggested that an increase in the number of roots and their diameters that cross the shear plane reach greater displacement before the peak shear force. The research of De Baets *et al*. (2008) and Guisasola *et al.* (2009) complemented these findings.

De Baets *et al.* (2008) explored the mechanism of root reinforcement and demonstrated that roots provided increased resistance to shear through a build-up of tensile resistance. This was tested using roots of Mediterranean grass and plant species. The roots were stretched between two clamps using a tensile tester to measure load and displacement. This showed that the roots provided increased resistance to tensile forces, building as the root is stretched and providing soil cohesion.

The laboratory study of Guisasola *et al.* (2009) investigated triaxial soil testing and compared the physical results against equations on the subject matter. Turfed and unturfed sand and clay loam soils were placed in cylindrical samples at specific densities and water contents. The testing either increased compression to a target pressure or an axial deformation was applied to twist the sample. Results suggested that in sandy soils the roots did not increase shear strength significantly compared with bare samples. However, root reinforcement allowed greater shear displacements before ultimate shear failure occurred. Clay loam properties were more dependent on increasing water content and the electrostatic force present. The roots were not evenly distributed, which could have an effect on the physical results compared with the calculations. However, the roots are suggested to limit vertical composite stiffness. The grass coverage and leaf height was investigated by Caple *et al.* (2011) to determine mechanical properties (absorption/energy return) of the turf. The study was conducted in a laboratory, creating a clay loam and a high sand content rootzone soil tank that was seeded with perennial ryegrass. Before testing commenced the samples were transported outside for 4 months and environmental conditions monitored. The grass was maintained at 50 mm for experimentation where it would be tested with a CIH. The grass was then cut to 25 mm and retested. Results showed the presence of grass was more important than the specific grass height. The grass absorbed some impact energy from a lighter mass 0.5 kg CIH on the first drop, but this ceased when the grass was flattened by repeated impacting. However, for the 2.25 kg CIH the soil conditions were a more dependent factor than the grass.

3.6 MEASUREMENT OF SURFACE PERFORMANCE

This section details the devices used for testing of sports surfaces and can be applied to sports turf. The section first details the current standardised test devices used to measure sports turf. There is then an overview of the available devices which either determine or can potentially be used to determine shear strength of sports turf, mentioning some of their shortfalls in terms of supplying shear stability results similar to those witnessed on sports pitches during player/surface interactions in rugby (see Section 1.2.2). The current agronomy tests are then detailed and a summary overview of the currently available equipment is given in the literature summary (Section 3.9).

3.6.1 STANDARDISED SURFACE TESTING DEVICES

The PQS framework, discussed in Section 1.2.3, created benchmarks for assessment of natural sports pitches. It introduced the RTD test for measuring surface resistance and the CIH test for ground hardness. The FIFA Standard (FIFA, 2015) and European Standard (EN)/British Standard (BS) (British Standards Institution, 2017a) which are based on the PQS, introduced the use of the Advanced Artificial Athlete (AAA).

Rotational Traction (RTD) (Figure 14): Described in BS 7044-1 1991 (British Standards Institution, 2007b) possesses a shaft of 46 kg mass, accommodating a torque wrench at the top and a 150 mm diameter disk with six studs in contact with the sports surface. The procedure raises the disk to 60 mm dropping it, to penetrate the ground with the studs. Rotational force is produced by turning the wrench 180° creating resistance between the studs and the surface, generating a torque value which assesses the shear strength of the near sports surface.

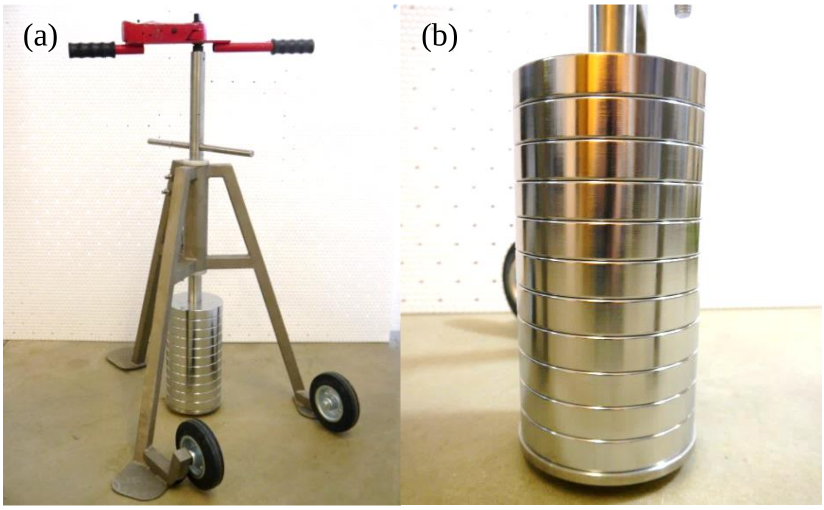


Figure 14 – The RTD (a) full device: (b) the rotational disk and 46 kg mass

Clegg Impact Hammer (CIH) (Figure 15a): The American Standard Test Method (ASTM) organisation details testing with the CIH (ASTM standards, 2002). A 2.25 kg weight (0.5 kg also used) is raised 450 mm and dropped onto the surface. An accelerometer in the weight determines the peak deceleration on impact converting it into a gravities (G) reading.

Advanced Artificial Athlete (AAA) (Figure 15b): Developed from the Artificial Athlete, the AAA is a 20 kg mass attached to a stiff calibrated spring and contact plate (70 mm diameter) which makes contact with the surface during testing. The mass is dropped vertically from a height of 55 mm onto the surface. There are three drops per test position, the mass is lifted into position with a 30 second recovery between the drops. An accelerometer located above the spring determines shock absorption (SA), (British Standards Institution, 2003), vertical deformation (VD), (British Standards Institution, 2005) and energy restitution (ER). It is the method approved by FIFA and World Rugby for testing SA and VD.

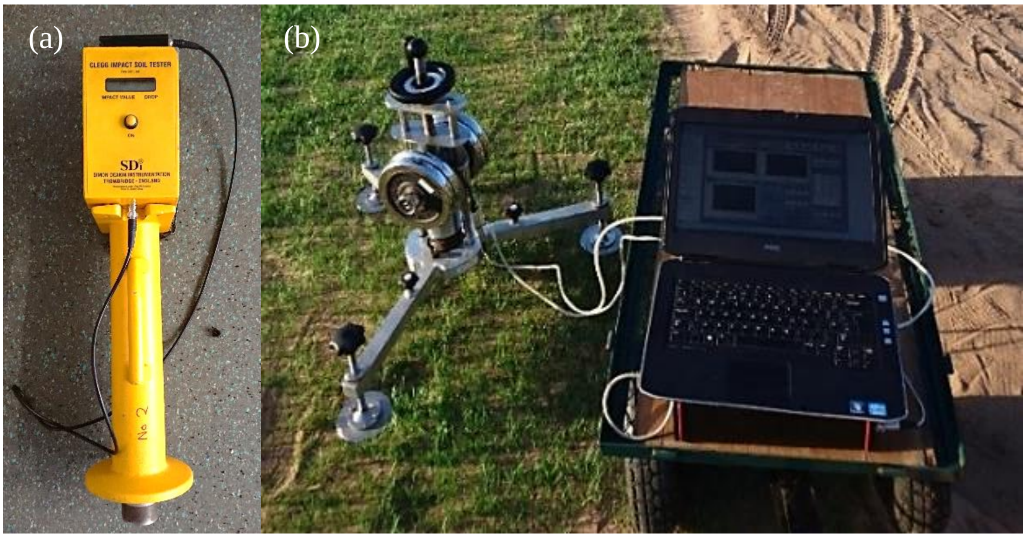


Figure 15 – The (a) 2.25 kg Clegg impact hammer and (b) AAA device

3.6.2 Related Shear Strength Devices

Going Stick™ (Figure 16): The Going Stick™ (TurfTrax Ltd, Cambridgeshire, UK) was developed for the assessment of horse racing track ‘going’. Used by racetracks to inform surface state for race day, horse trainers and maintenance. It is a simple, portable tool resembling a garden spade handle with a single metal probe (100 mm long by 21 mm wide) at the base. For a standard ‘going’ test the probe is pushed into the ground to 100 mm and then pulled back by the operator to approximately 45° to derive an instrumented going number from a calculation combining the penetration and shear resistances. This device has proved useful in measuring clay in the deeper shear stability failure zone but lacks the confinement to test sand accurately (see section 3.7).

Figure 16 – The Going Stick

Clegg Shear Tester: A shearing field test similar to the Going Stick™ was termed the 'Clegg Shear Tester'. It however appears that this product has not been commercialised or has not been reported since the study it was used for (Sherratt, Street and Gardner, 2005). The prototype device comprised a frame with a footplate for the operator to stand on, providing some soil confinement, and a lever attached to a metal plate of size 50 mm by 30 mm. The plate is inserted vertically into the ground and the operator pulls the lever manually to rotate the plate from a vertical to horizontal position, through 90°, shearing the zone of turf in front of the plate. An index value is displayed on the readout which is claimed to represent the shear strength of the turf system. This product showed potential because of to its testing of shear stability to depth and confinement, however, as stated in the introduction, failures were witnessed up to 100 mm and so this device could not assess the full range of shear instability of turf.

Hoof Drop Hammer (HDH) (Peterson, Wayne McIlwraith and Reiser, 2008): The high mass and force of the scrum was relatable to the forces seen in horse racing, therefore the HDH was investigated. This apparatus system makes it possible to load the surface at the rate and loads that are applied by a horse at a gallop, reaching loads up to 14 kN. The HDH mimics the point at which the fore limb contacts the track and the weight of the horse is transferred to the hoof. This is the period where both the highest vertical loads and the highest shear loads are applied to the soil. Due to wide geographical distribution of horse racing venues the apparatus could be transported, assembled and mounted on a mobile platform on a vehicle at the track. The movement of a horse's hoof from visual inspection when in contact with the surface looked to be similar to that of a rugby player in the scrummage (Section 3.8.3) and so the moment was regarded useful. However, issues with the device were that the results were not fully translatable as horse race courses are far softer than sports turf surface (Caple, James and Bartlett, 2013). The device, with its bulky weight and the fact it needs to be attached to a vehicle for testing, would be impractical for high performance sports turf pitches (discussed in device specification Section 4.2.1).

Divot Tester (Serensits, McNitt and Petrunak, 2011): This is a simplistic test where a golf club pitching wedge is attached to a pendulum (76 kg). The golf club is adjusted to the same level above the surface at every test point. As the pendulum swings a divot is made on the soil surfaces by the golf club and this length is measured. The length of the divot is an empirical method of measuring the shear strength of the turfgrass, which shows differences in strength with divot length. A useful simplistic test, however, it cannot test deeper into the rootzone or be altered to test the different depths that associated with the sought-after shear stability.

PennFOOT and Other Similar Apparatus (Caple, 2011): Caple (2011) lists a number of devices that are developments of the RTD. The PennFOOT and similar devices are portable apparatus transported on wheels and are used to assess *in-situ* surfaces. The devices allow measurement of both translational and rotational traction, on a variety of shoes/boots, and variation in the normal force applied. However, the devices' movements applied are not based on movements performed by athletes, leaving uncertainty to how the shoe-boot behaviour relates under athlete-specific movements. Additionally, these devices are only investigating the near surface of the turf and not deeper shear stability.

Carochran Sod Puller (Sorochan and Rogers, 2000): A sample of turf is removed from the ground and inserts onto a platform on the Carochran Sod Puller. Four metal bars 10 cm wide and threaded with 29 8 mm metal golf spikes are then used to clamp the turf to the platform. A battery-powered hydraulic pulley then pulls the turfgrass platform at a constant rate, shearing it against the clamped bars and spikes. The spikes' resistance during pulling is measured with a load cell. The issue with this method is that it is grass strength that is tested opposed to the full turf and rootzone structure. The soil texture properties such as density can be affected by removing it from the sports turf and so it does not create an accurate representation of the deeper shear stability.

Shear Vane: The Shear Vane BS 1377-7:1990 (British Standards Institution, 1990b) is a portable test used widely in laboratory and field assessment of clay soils and known to be used in a number of pitch investigation studies. The vane has a rod length twice the overall blade width and creates minimal disturbance as its passes into the ground. There are four blades that are as thin as possible, pushed into the material, with the vane size dictated by the predicted shear strength range. During the procedure the vane is inserted, and the head is rotated building resistance until the soil fails. A mechanical gauge measures the shear strength created by the soil. The Shear Vane although able to test to different depths successfully, it suffers from the same issues as the Going Stick™ and lacks confinement to test granular sandy soils.

Shear Box Test: The shear box is a laboratory test (British Standards Institution, 1990b) that measures the shearing resistance by inserting soil into a box and restraining it. This is then mechanically induced along the horizontal plane while pressure is applied normal to that plane. The shearing resistance is measured at regular intervals of displacement and failure occurs when shearing resistance reaches a maximum value for the soil. This apparatus is bulky and to be tested the sample has to be removed from the *in-situ* location affecting the rootzones structure.

3.6.3 **AGRONOMIC TESTS**

The agronomic tests given below are used to determine the grasses characteristics, water content and the densities of the turf/rootzone. They are used for the PQS and the Scoreplay™ tests.

Corer (Figure 17a): The corer is a hollow, cylindrical, 44 mm diameter, 200 mm long tube that is bored vertically into the sports pitch and removed to retrieve a soil sample. One side of the core opens allowing visual inspection of the soil texture and grass rooting. Soil texture samples can be removed from the core and tested for gravimetric water content (BS EN ISO

11461:2014; British Standards Institution, 2014), bulk or dry density (BS EN ISO 11272: 2017; British Standards Institution, 2017b) and particle density (BS 1377-4:1990; ISO/DIS 11508:2016; British Standards Institution, 1990; International Organization for Standardization, 2016).

Quadrat (Figure 17b): A grid of similar sized quartile squares are present in a rectangular frame. These grid areas are used to subjectively identify the amount of grass coverage in a given area creating a coverage percentage value.

Figure 17 – The (a) corer and (b) quadrat

Mirrored Prism (Figure 18a): This test measures grass height. This was primarily utilised for artificial turf (FIFA, 2015) but has been applied to natural turf. A rectangular prism with a mirror angled 45° to vertical is laid on the natural turf surface. The vertical view allows the operator to determine the height of the grass blade via a scale placed on the prism backing. The average grass height is produced by analysing the blade height of numerous grass tips.

TDR Moisture Probe (Figure 18b): The device measures volumetric water content of the soil. Four tines, 50 mm in length are inserted into the soil to determine the dielectric permittivity of a medium by measuring the time it takes for an electromagnetic wave to propagate along a transmission line surrounded by the medium. The transit time for an electromagnetic pulse to travel the length of a transmission line and return is related to the dielectric permittivity of the medium, proportional to the square of the transit time. The time and speed of travel of reflected signal from the end of the probe varies with the dielectric of the soil, which is related to the water content of the soil (Topp, Davis and Annan, 1980; Ventrella *et al.*, 2008).

Figure 18 – (a) A mirrored prism to identify grass height and (b) a TDR moisture probe

3.7 SURFACE PERFORMANCE TESTING DEVICES

The surface devices described in Section 2.5 were used in a number of studies to determine their suitability on natural turf.

The CIH has been used in many studies to assess surface hardness conditions. The ASTM standard recommends one drop per test as it is more relatable to player interaction (ASTM, 2010). However, the 2.25 kg CIH missile has not been shown to replicate any specific impacts or peak ground reaction force (GRF) that occur on sports field surfaces and must be regarded solely as a device providing a generic value of surface conditions (Young and Fleming, 2007; Ford, 2013). Twomey *et al.* (2014) and Caple *et al.* (2012b) investigated how the number of drops on the same position of natural turf affected the results. Twomey *et al.* showed significance between drops one and two compared with further drops and Caple determined that the third drop was the least variable. It was stated that the greater the number of drops the closer the particles will be pushed together, compacting the surface and representing more accurately the mechanical properties of the surface than of grass coverage (Caple *et al.* 2011).

With repeated drops the device may measures differences in deeper soil profiles (Gibbs *et al.*, 2000). A safe range of hardness for gravities (G) on natural turf surfaces is not stated in the ASTM standard. However, this ranges from the PQS of 35–120 G. Ford (2013) comments on the safe working ranges suggested by studies indicating acceptable ranges to be between 60 G and 95 G. with maximum limits set between 150 G and 200 G.

The RTD measures the rotational traction of natural and synthetic sports surfaces and has been the standardised test device since the 1990s (Paper 3, Section 1.2). The device has been useful on sports surfaces as it is a simplistic method of determining the resistance of the turf, representing a studded boot turning on the surface. Excessive traction from surfaces and foot fixation is a cause for player injury (Caple, James and Bartlett, 2012) and so its measurement is an important factor. However, it lacks reliability, providing an unrealistic static load compared with large vertical loads of players and the rotation (more than 40°) is unrealistic compared with a player’s rotational movement (Paper 3, Section 1.2). The PQS states a minimum of 20 Nm and FIFA suggested a safe range of maximum of 25–50 Nm (FIFA, 2006, 2015). Further studies on Australian football fields study suggest an acceptable range between 21 Nm and 74 Nm (Twomey *et al.*, 2013).

The Going Stick™ has shown a relation to the impact of the CIH when it is penetrating the surface and traction of the RTD when it is shearing the soil (Caple, James and Bartlett, 2013). These results were discussed in Paper 1, Section 4 as, although clay-based soils showed relation to shear strength the Going Stick™ may not accurately assess sandy soils under the same confinement as player interaction. The Shear Vane has similar issues and although it has been used in numerous studies, its suitability in unconfined sandy soils might not replicate shear strength effectively comparable to player loading on the surface (Paper 1, Section 4; Paper 3, Section 1.2).

The laboratory shear box test is a useful and trusted method to assess soils shear stability and angular friction. However, *in-situ* soil retrieved from sports turf pitches can be hard to maintain or replicate conditions when disturbed (densities and water content) (Paper 3, Section 5.1). The shear box was adapted to *in-situ* testing by Comino (2009). As discussed in Section 3.5, the device incorporated a frame and a hydraulic jack providing useful data of grass plots.

The AAA has not been used widely in natural turf studies. Vertical loading of an athlete is suggested to be replicated by the AAA, however, there are no studies that test this on natural turf surfaces. The FR and VD have been used to benchmark standards for artificial turf systems (Caple *et al.*, 2011; FIFA, 2015); however, little is known about the meaningfulness of the results on natural turf.

The devices discussed can assess the conditions of ground surfaces although, as stated throughout the text, it is widely documented that they do not biomechanically fully replicate player interaction with a sport's surface (Young and Fleming, 2007; Caple *et al.*, 2011; Damm, Stiles and Dixon, 2015). There is also suggestion that the PQS framework is no longer suitable for the current natural or hybrid sports pitch and should be re-evaluated, benchmarking against player and technological development (Caple, James and Bartlett, 2012a).

3.8 PLAYER-SURFACE INTERACTION

Optimal conditions for player interaction are important to maintain performance. Therefore, monitoring player interactions with the surface is of great importance. The athlete's interaction with and perception of a variety of sports turf (natural and artificial) surfaces when running and/or turning in different footwear is common place. However, few studies focus on the turf reaction of this impact. This section focuses principally on this area, including studies on rugby scrummage forces as they can generate the largest magnitudes, although these studies do not include GRF.

Many sports have progressed with modern technologies (Haake, 2009). Focusing on Football and Rugby Union, this was seen by the advancement in technologies in player's apparel, the equipment used in the sport and the technologies to adjudicate the current versions of the games. The other notable factors are the improvement in player nutrition and exercise that has transformed the players' physical anatomy to optimal conditions for the sport (Pelly *et al.*, 2014; Fredericson, 2016). This is evident in rugby as players are becoming larger and stronger (Fuller *et al.*, 2013; Trewartha *et al.*, 2015; Jones, Hennessy and Hardman, 2017). These effects suggest there may be greater strain on sports surfaces as they are subjected to greater forces than witnessed in the past generations.

3.8.1 Player Interaction with the Natural Sports Surface

In general, vertical GRF and collision force is approximately 1.5 to 3 times body weight – within the first 50 milliseconds (ms) of stance (Lieberman *et al.*, 2010). James *et al. (2006),* Stiles *et al.* (2011) and Smith *et al.* (2004) all investigated the effects that running and turning have on turf and soils.

James *et al.* (2006) and Stiles *et al.* (2011) undertook similar studies investigating players running/turning on a constructed soil surface in a laboratory environment. James *et al.* (2006) investigated the dynamic response at different depths in the soil of the players' loading during running across a turf rootzone. Soil pressure transducers were placed at depths of 100 mm, 200 mm and 350 mm into a sandy clay loam rootzone (controlled soil density of 1.46 g/cm^3 and 1.59 g/cm^3 and dimensions 20 m long, 1.8 m wide and 1 m deep) testing channel. Vertical stress and in shoe pressures were collected for the participants running across the soil at 4 m/s. Between different densities there was no difference in the loading rate, but to a depth of 100 mm the soil was significantly more reactive to the surface loading than at 200 mm. The loading rate of the player was also linear to the player body weight where increased weight increased the loading.

Stiles *et al.* (2011) measured the human response to running and turning on a (29 mm cut) ryegrass seeded soil mediums (clay, sandy loam and sandy rootzone). The turf was inserted into trays to form a 9 m runway with a force plate present underneath one of the trays. Participants would either run (3.83 m/s constant speed) across the surface or turn, planting their foot at 90° to the direction they were running and then undertaking a standardised 180° turning movement, pushing off on the foot contacting the force plate tray (right foot run). The study showed that after running or turning, clay would harden, and more so with higher loading, thus increasing the shear strength, while the sand's shear strength would remain unaffected. The peak loading was much greater in the looser sand surface, at 101.48 body weights per second (BW/s). The turf needed to be monitored carefully as wear of the turfgrass was commonly seen with player interaction. This was problematic as the turf surface was not constant throughout the study, which could affect surface properties and player interaction (Ford, 2013).

Smith *et al.* (2004) incorporated force-plates 35 mm beneath an imported rootzone natural turf to alleviate the hindrances of laboratory-based measurements, and the turf could be replaced when damaged. Water content was measured to remain constant throughout testing. Players performed slow (4.4 m/s) and fast (5.4 m/s) running with shoes and football boots. Results showed that at fast pace in football boots there were greater peak vertical impacts (2.7 BW or 26.09 BW/s) than in trainers.

3.8.2 THE RUGBY SCRUMMAGE

The heavier general rugby player is commonly around 110 kg (Paper 2, Section 2) and it has been widely documented in past literature that the higher pack mass increases the scrummage force (Trewartha *et al.*, 2015). However, recent studies have suggested that compressive forces are not dependent on mass and that muscle mass may be a better predictor of scrummaging force (Preatoni *et al.*, 2013; Green *et al.*, 2017).

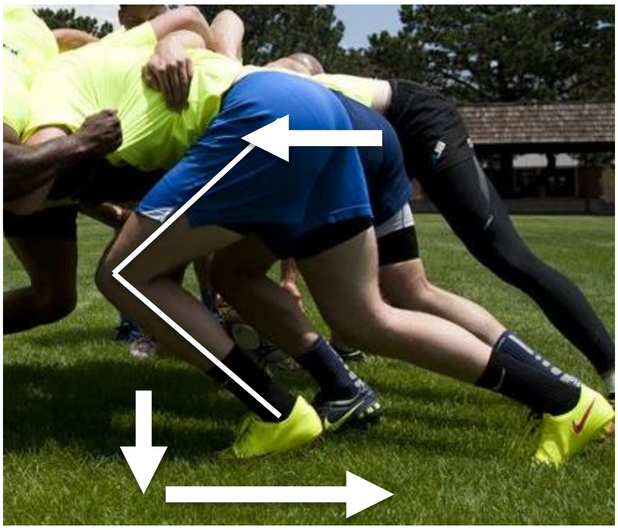


Figure 19 – Body position showing the biomechanical position of the leg during scrummaging

A number of studies have used a pack or an individual pushing against an instrumented scrum machine to calculate forces. These studies measure the force applied in a horizontal direction, however, some also have been measured vertically. Figure 19 shows the general leg position of a player in the scrum and the directions of force the player applied forward and to the surface. Table 6 refers to the Trewartha *et al.* (2015) study, with several additional literature findings. The peak horizontal impact loading forces found from a pack during engagement can vary from 9.8 kN to 16.5 kN for international/professional players. There are sustained horizontal compression forces ranging from 3.4 kN to 8.3 kN dependent on the level of rugby (school, women, professional) and the rulings used (Saletti *et al.*, 2013; Trewartha *et al.*, 2015). When investigating individual players Quarrie & Wilson (2000) found that, on average, the scrummage is 65% of the sum of individual forces. Du Toit *et al.* (2005) recorded an engagement of 10 kN across the front row when pushing and Milburn (1993) found that the front row produced the greatest percentage of scrum force of the pack (42%).

These experiments revealed that horizontal forces are highest compared with vertical downward forces. During the engagement phase vertical forces have been registered as ~ 1 kN and ~ 3.9 kN and during compression ~ 1.5 kN (Trewartha *et al.*, 2015). The lateral forces produced by the scrummage machine's displacement were lower magnitude than the compressive and vertical forces with inconsistent direction (Preatoni *et al.* 2013).

Although the studies highlight downward forces, there are currently no biomechanical studies measuring a player's foot force vectors either in the scrum or on natural turfgrass. However, from visual inspection of back-row players in the scrum, where there is the most evident failure, the front foot and studs begin by penetrating into the turf (Figure 20). As the player pushes forward during the scrummage they rotate their foot, lifting their heel and applying more force to the fore foot. Continued application of pushing force forward consequently rotated the two front studs (as detailed in Paper 2, Section 2). The foot was found to rotate by around 40° in the movement of the foot. Past this rotation the turfgrass was usually found to fail underneath the player interaction on the surface. Future studies investigating the effect turfgrass quality has on the forces produced in the scrum would be beneficial, in addition to available literature detailing the amount of pressure the players feet generate on the surface. The only available study of the action of the foot in the rugby scrummage was reviewed by Milburn (1993), investigating players pushing in different body alignments against a ground force plate and demonstrated that the resultant force vector for the feet was never greater than 27° to horizontal. The closest available foot position to a rugby player's is when an athlete is in the blocks during a sprint start. Similar to a rugby player, they require an explosive movement and it has been found that a single leg (front) can produce 1.7 kN onto the block (Fortier *et al.*, 2005).

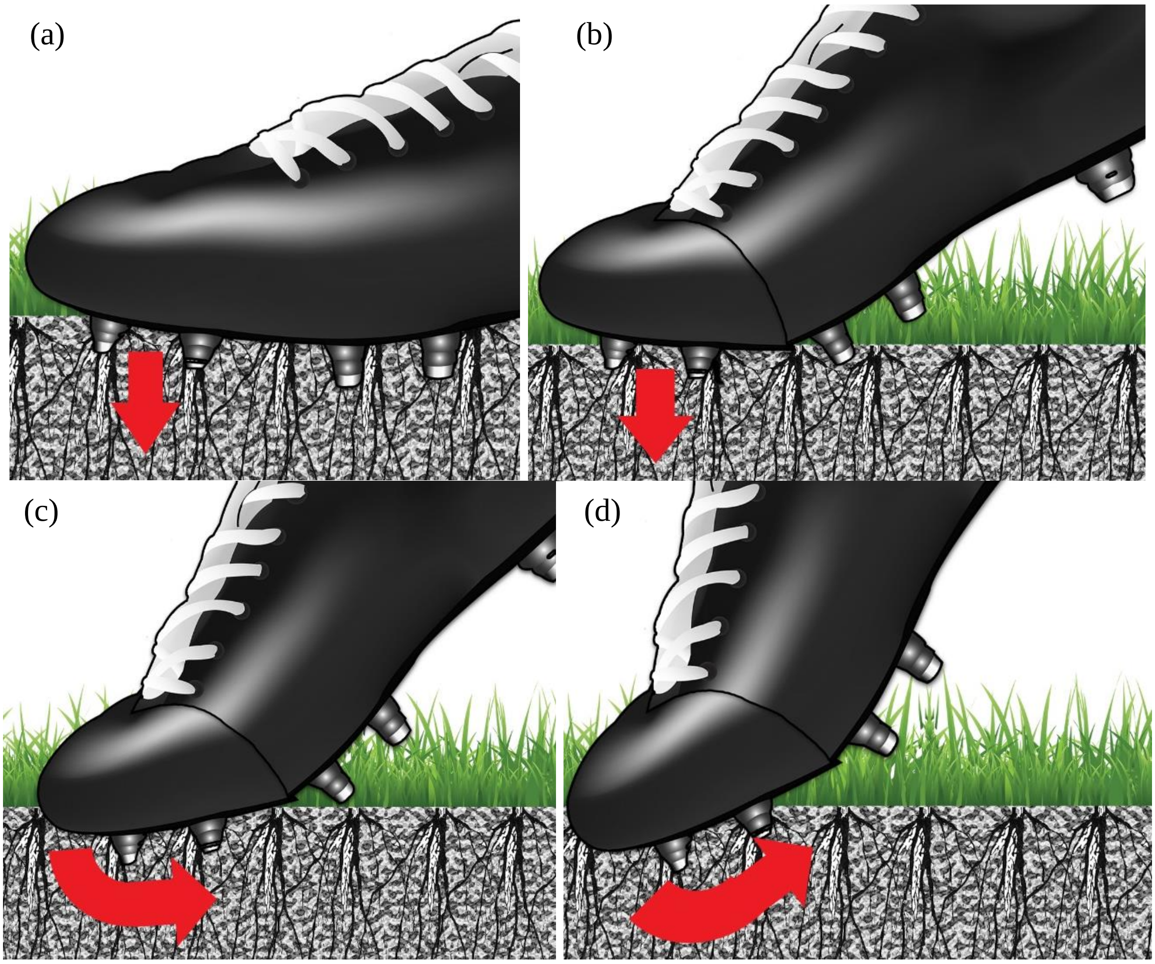


Figure 20 – Player boot-surface interaction during scrummaging, pushing against the opposition pack

Furthermore, in an attempt to make rugby safer and easier to referee, the scrum rules have been updated (World Rugby, 2017). From 2013, players now bind and lean against each other before force is applied. This has removed some of the impact of the scrum engagement, although, it still produces peak compression energy or force but with less risk of neck injury (Jones, Hennessy and Hardman, 2017). Therefore, the peak force may have reduced but the average sustained compression forces may remain similar to the current scrum model.

Table 6 – Studies measuring scrum forces

		Engagement Force (N)			Sustained Force (N)		
Study	Level	Horizontal Compression	Peak Vertical	Peak Lateral	Horizontal Compression	Peak Vertical	Peak Lateral
Milburn (1990)	School	4430	-940	-150	3370	190	-3040
	University	6540	-160	-730	4610	610	-1510
	Amateur	5630	-868	-2413	4300	-151	-3093
	International	7982	2268	-85	5761	1305	-340
Rodano *et al*. (1992)	International U19	-11400	-440	-400			
L. Quarrie & Wilson (2000)	Amateur	11000			7170		
Du Toit *et al*. (2005)	School	7526			6145		
Retiere (2010)	International U19	~ 12000	~ 1500		~ 7000	~ 200	
Saletti *et al*. (2013)	Professional	13000					
Preatoni *et al*. (2013)	School	9100	-2000	1100	4880	100	110
	University	11700	-2900	1300	5940	96	130
	Women	8700	-2400	1000	4790	7	-90
	Amateur	12000	-2300	1400	5780	-28	110
	Professional	16500	-3900	1900	8300	720	620
	International	16500	-3600	1900	8300	1084	600
Cazzola *et al*. (2015)	Professional	9800					
Green *et al*. (2016)	Amateur (Individual)	2730					

3.9 SUMMARY

The literature review was used to achieve objectives 1 and 2. The finding of the literature suggest that turfgrass construction and differences in their variables (grass rooting, density and water content) can influence their shear stability/strength. These properties are constantly changing and consequently it is hard to determine the effects of each variable through *in-situ* testing. To measure the influence of certain properties therefore, there needs to be some control of the variables or their influence must be better understood for each soil texture. Hybrid systems have been suggested to improve stability and have shown some improvement over natural sports surfaces. However, no studies were found that compare the different hybrid systems with each other.

Furthermore, the standardised and related equipment used to measure shear strength has found shortfalls in their assessment to measure the stability of sports turf at the depth required, as stated in Section 1.2.2. The RTD device, which has problems with test repeatability, can also only measure the near-surface interaction similar to the PenFOOT, Divot Tester and other similar apparatus. The shear box and the sod tester created issues as moving or extracting the rootzone would alter it from *in-situ* conditions and the HDH, although having potential lacked portability and was impractical for sports turfgrass pitch assessment. The Going Stick™ and Shear Vane provide realistic values for clay-based turf to depth; however, as they do not produce confinement to the surface they are ineffective for sand-based constructions. Research on surface performance tests showed most have limited repeatability and lacked relatability of surface/player interaction forces. In addition, there are no readily available papers on player boot–surface interactions during rugby scrummage. Therefore, the concept design can encompass some of the design features of current equipment but would need to be able to measure to different depths up to 100 mm, be able to confine the sports turf to allow it to test sandy soils, be suitable for portable testing of the elite sports turf and attempt to better recreate a players foot and stud movement through the rootzone and turf. These issues were all encompassed in the design process of the shear stability device discussed in the next section.

4 THE RESEARCH UNDERTAKEN

4.1 RESEARCH INTRODUCTION

This chapter follows the work packages described in the methodology (Sections 2.3.2 and 2.3.3). It is divided into two parts, with the first part detailing development of the prototype and the second part investigating the variables deemed by the literature to affect shear stability.

Initially, in order to meet objective 3, a design process was undertaken to produce the prototype device, the 'Shear Tester'. With reference to Pugh (1991), this section discusses the logical stages of progression that the device underwent to obtain a product that could measure shear stability on natural and hybrid turf to the deeper depth than currently available tests. This would see review of the literature and detailed Labosport input placed into a specification, which theorised a number of concepts before the final design was chosen. The chosen device was then manufactured, producing a device to be trialled (which is reported throughout Paper 2), altered and validated (disclosed in Paper 3). The validation saw the device tested in controlled laboratory soil textures of known variables and production of an improved device to better assess the devices mechanical properties.

To better understand the variables shown to affect shear stability of turf (objective 4). The common variables were then tested in larger studies with the Shear Tester devices. These studies were used to identify the influence of grass plant establishment, water content and density of different soil textures and construction types. The raw information would be statistically analysed with correlation and regression to find statistical significance between the Shear Tester results and the variables, which are discussed in Section 5.

4.2 SHEAR TESTER DESIGN AND DEVELOPMENT

Section 3.6.2 evaluated devices that showed the potential to be used for natural sports turf assessment. The GoingStick™ which showed the most promise, was tested throughout Paper

1; however, similar to all the other devices it could not provide suitable shear stability assessment across the range of natural and hybrid sports turf commonly used (Paper 1, Section 4).The problem for all devices tested was either they could not assess deeper than the near-surface of the turf, the turf had to be removed from *in-situ*, the equipment was too heavy or the device could not actively confine the ground. Therefore, a device design was developed with the methodology (Section 2.3.2) to better assess sports turf shear stability. This method ensured that the information gathered created a highly specified rigorous design process to create an effective design. Figure 21 details the design process flowchart and the included work packages of each stage (discussed in their associated section). The 'sell' stage of the process refers to the impact on the sponsor and is discussed fully in the conclusions (Section 5).

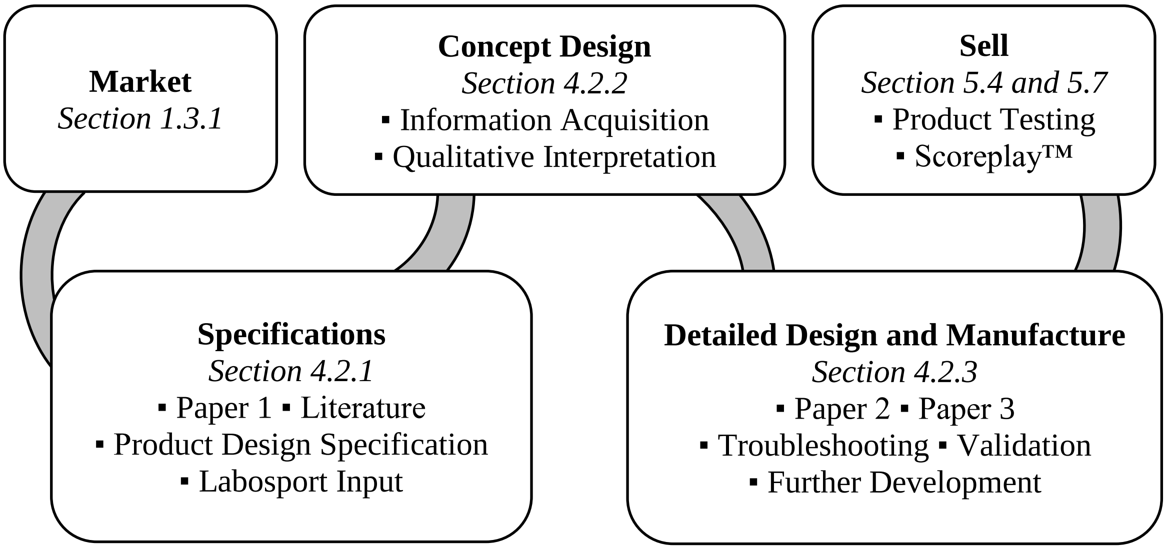


Figure 21 – Product development flow chart

4.2.1 SPECIFICATIONS

The key inputs for the specification were tailored by Labosport's input and moulded around the objectives stated. Inputs from Labosport, detailed that the device should be a simple mechanical test to meet a defined project budget, which was portable both in testing and transit, and provided easy to interpret results that could be easily reproduced (stated in Paper 2, Section 2). From specifications brought forward by the review of the literature (discussed in Section 3.9), this meant that the main factor required for the device was measurement of shear stability of the turf and rootzone to depth up to 100 mm, a quality many current devices lack. Paper 1, Section 4 showed that even when measuring to depth it was possible that confinement could be a problem in some materials and so confining the surface would be required in the design. It was also detailed that many of the current tests lack repeatability and similarity to player interaction, therefore the assessment method should be more relatable to player foot interaction/forces across the range of soil textures.

All these design factors were considered and inserted into a product design specification (PDS) with reference to Pugh (1991). This would consider all aspects of the product questioning and countering features regarding the functionality of the device (Appendix J). The outcomes produced the key specifications, which are presented in Figure 22 and discussed further in this section.

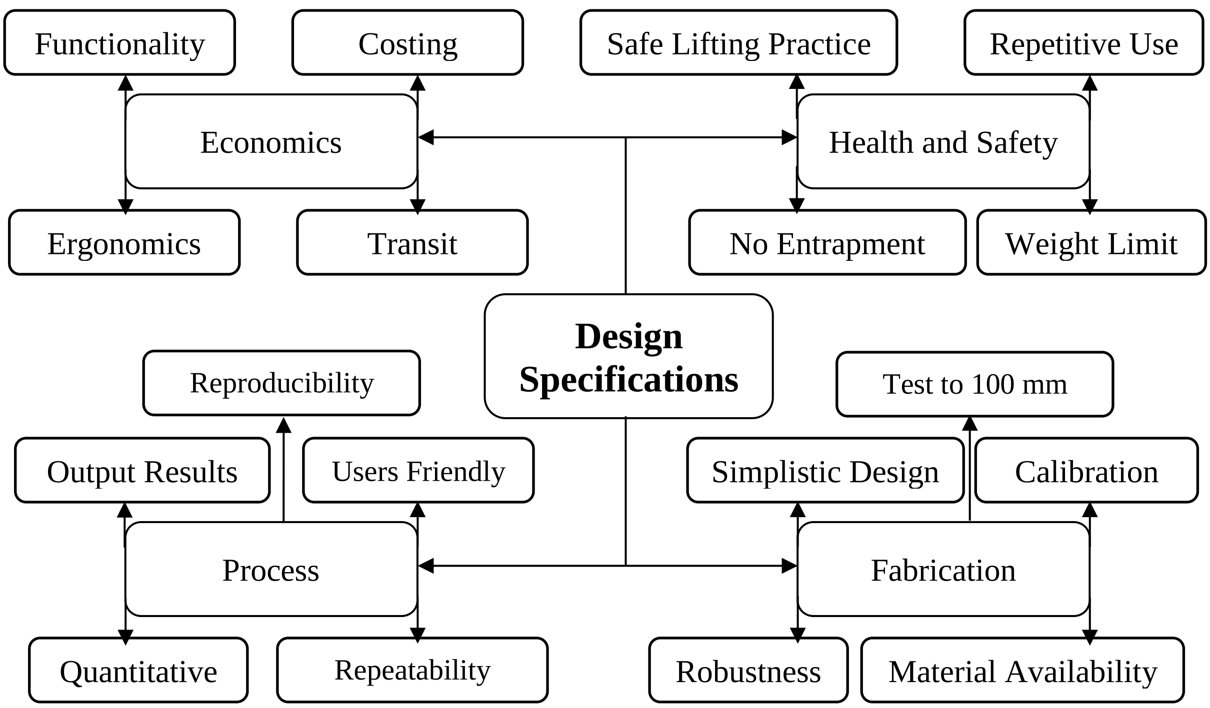


Figure 22 – Design specifications and considerations when developing the concept device

- Repeatability and Reproducibility – As stated in the methodology (see Section 2.3.3), during experimentation the device required a repeatable and reproducible method so that whether retesting in a different position or during a later test session, all results adhered to a specific procedure. This would require a detailed but easily understandable method procedure plan for the device.

  - Device Output – The results produced from the device should measure up to 100 mm depth into the turf and have an analysis method that is easily understandable. This includes digital monitoring solutions for rigour of the research.

  - Automated Test – As reported widely, many surface performance test equipment has poor test repeatability (Section 3.7). The concept device would therefore incorporate automated test parts to provide better test repeatability.

- Ergonomics – The test needed to better resemble the replication of a player's boot/stud in a rugby scrum, more so than current apparatus, but would also incorporate features to allow transport and effective operator use of the device.

  - Transit – The device mass could not be so heavy that it could not be used effectively in testing but also in transit worldwide, and therefore could be capable of transport by air. Sports surface test equipment currently can be up to 47 kg (Section 3.7) and therefore a lighter device than this is deemed suitable. The device would also incorporate a means of effective movement around site to aid operator health and safety.

  - Functionality – No complex parts were included that could be easily broken or function incorrectly. The device function was easily interpreted and suitable for all operators to undertake the testing.

- Cost – Labosport set a budget for the design, development and manufacture of the device. The project budget formed what was possible for inclusion in the device.

- Fabrication – The device was designed with aid of Loughborough technicians who would fabricate the device. The device was required to test the high forces seen in scrummaging and, after considering the other specifications, suitable materials and design were confirmed, and the device was manufactured. The design schematics were kept so future models could be fabricated.

4.2.2 DESIGN CONCEPT

Progressing from the specifications, several concepts were created that were appropriately scored on their individual characteristics and to what regard they met the specifications (Table 7). The designs are briefly outlined with further explanation of the chosen device after the design concepts were scored with the concept matrix (Table 7).

Push Pin Concept: In the model (Figure 23), pins would be pushed into the 50 mm or 100 mm test depth required, depending on the required failure investigation (See section 1.2.2). When at the correct depth, the device has an automated gearing system powered by a motor. As the machine body slowly descends to the ground the movement slowly pushes the pins apart and drives them upwards through the soil and turf. The pins have strain gauges that record the force as the pins move through the soil. The device weight would be provided by the stainless-steel pins, battery, electronics and frame; however, the overall mass would allow the device to be easily transported by hand during testing.

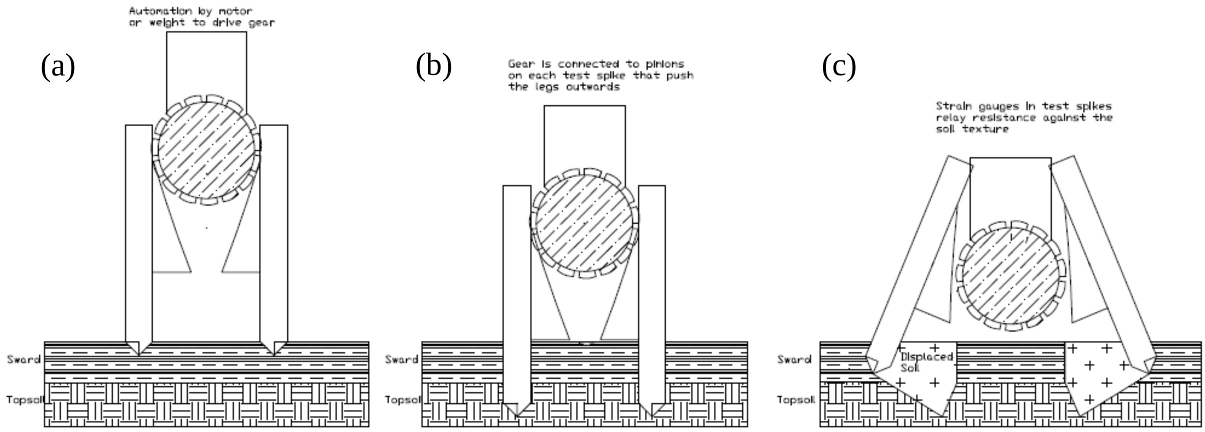


Figure 23 – Push Pin device using a gear system to pull pins apart in the soil

<u>Rotational Concept</u>: The rotational concept (Figure 24) works on a similar mechanism to that of the RTD, however, the pin would be inserted to much greater depth into the turf in the required test area. The device legs would support a retractable weighted frame which can be set to test specific depths. Once in place the operator would secure the device by standing on a base plate located by the legs. The rotation would be automated with a motor and the torque value produced measuring the maximum torque value.

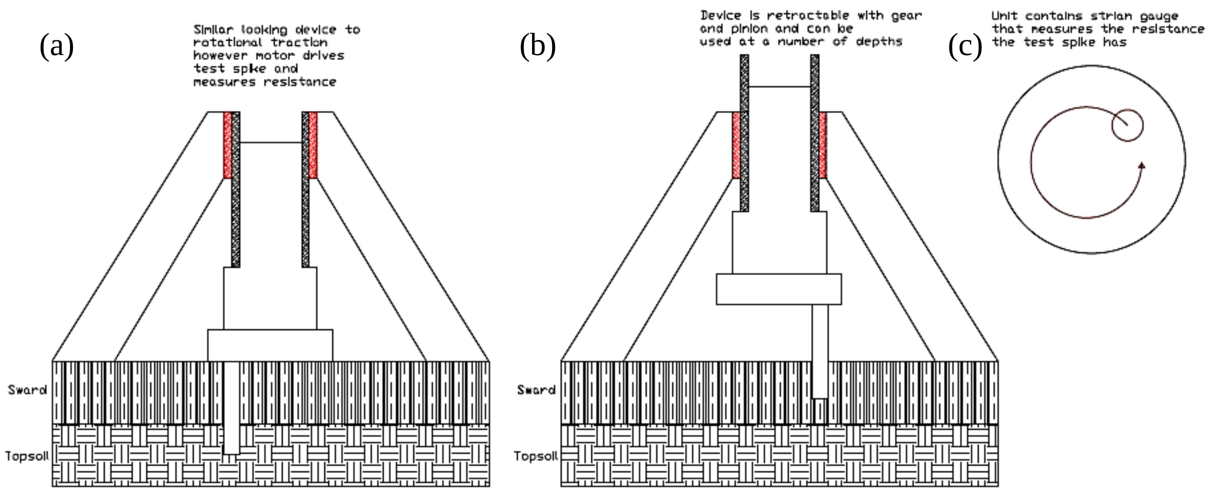


Figure 24 – Rotational concept design powered by a motor to create torque values

Drag Concept: The device looks similar to a golf buggy with a cylindrical weighted frame on the front (Figure 25). The device is portable with a back wheel which can be used when the device is not in operation. The drag test works by lifting the weighted cylindrical frame into an upright position, penetrating the studs/pins into the turf to a set limit and confining the area around the pin. When in the start position, the lever is pulled, and the device is allowed to fall under its own weight until the support wheel contacts the ground. Strain gauges monitor the force produced on the pins and record a result for the maximum force.

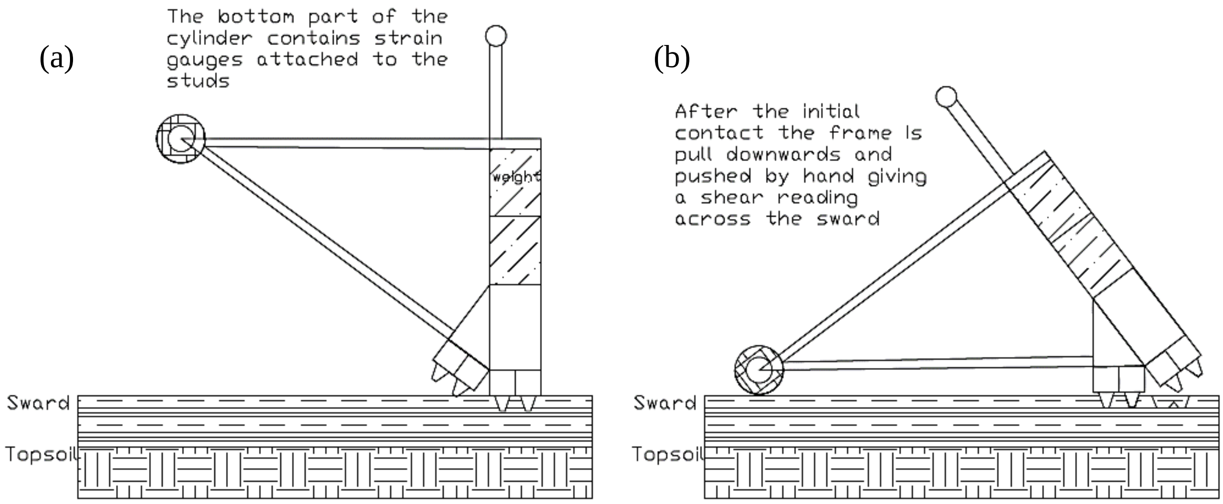


Figure 25 – Drag concept device is placed in position so its cylindrical mass in perpendicular to the ground. It is then rotated pulling the pins through the turf to a set depth.

Lever Arm Concept: This concept works on the principle of gravity to create movement of a pin inserted into the soil (Figure 26). The pin is inserted to the specific depth required and an arm is lifted into place. The arm is weighted and mass is added until the pin fails. This provides an empirical result produced from the weight placed on the arm. The area around the pin is confined by operator weight allowing assessment of sandy soils.

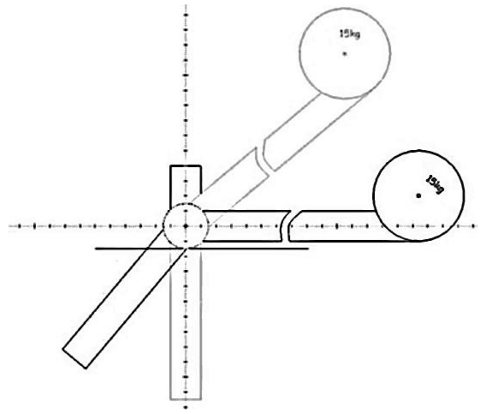


Figure 26 – A concept showing how the mass, lever arms and gravity would create movement in the soil

The design matrix used by Pugh (1991) was used to evaluate the different concepts and suggest the best design to progress, develop and manufacture. Table 7 shows the four design concepts, their scoring for each speciation criterion and their final rank. Each criterion was compared against currently available relatable apparatus (detailed in Section 3.6.2) and the concept devices are either scored as a plus (+), meaning they offer greater ability, zero (0), offering no difference, or (-), meaning they are worse than the current portfolio of an available tests when considering assessment of shear stability to depth.

	Portability (Transit)	Portability (Testing)	Test Parameters (≤100 mm)	Surface Confinement	Output Result	Mechanical Simplicity	Repeatability	Player/Surface Relatability	Reproducibility	Cost (low)	**Score (+/0/-)**	**Rank**
Push Pin	+	+	0	-	+	-	+	0	0	-	**4/3/3**	**3**
Rotational	+	0	+	+	-	-	+	-	0	-	**4/2/4**	**4**
Drag	0	+	-	+	0	+	0	+	+	+	**6/3/1**	**2**
Lever Arm	+	0	+	+	0	+	+	+	+	+	**8/2/0**	**1**

Table 7 – Pugh Concept Matrix for the four designs

The rankings suggested that the lever arm device met or was better than current tests across the criterion produced by the specifications (Section 4.2.1). After discussing the design with Labosport, the concept design was approved, and work was undertaken to manufacture the product. Details of the concept specifications are provided below; these shaped the detailed design of the equipment and created the reasoning for part of the design. The key design inclusions (also stated in Paper 2, Section 2) were:

- Testing the Turf / Rootzone – In the development of a novel way of shearing the soil to different depths and similar in force generation to player interaction, it was theorised that the probe would provide similar movement, albeit more simplistically. Currently, the surface performance test equipment lack relatability to player interaction (Section 3.7) this can in part be due to the high complexity between the movement/interaction of the leg, foot, footwear and the surface (Milburn and Barry, 1998). With no studies available that explored rugby scrummage foot biomechanics (Section 1.2.2), theorised movement was produced from visual inspection reviewing the front studs of a player's boot (see Section 3.8.2). During scrummaging, when recorded forces were highest (16.5 kg) (Preatoni *et al.*, 2013) and failure was common (Section 1.2.2), it was found that there was rotation of the stud from a vertical placement in the turf, moving upwards and rotating until, in a number of witnessed cases, the turf rips out and shear stability failure occurred. Therefore, to provide simplistic relationship to this observed instability, the device model would replicate a single stud of 20 mm cross-section diameter (World Rugby, 2015), but to exaggerated depth of the suspected failure zone up to 100 mm (Section 1.1). This pin would be inserted into the soil and force applied to pull it through a rotation similar to that of the stud. To better analyse the unknown shear stability failure depth for both the localised and larger area failure (discussed in Section 1.2.2), two pin test depths of 50 mm and 100 mm were considered. The single test pin opposed to multiple pins was preferred as the mechanism used to apply force would be less (aiding transit) and the greater simplification of the pin conceptual model calculations could be easier to understand.

- <u>Creating a Repeatable Test Procedure</u> – As stated in Section 3.7, many of the devices lack repeatability in their test procedure. This can create discrepancies in achieving the same result in the equivalent conditions. In order to limit this an automated method was incorporated into the design. The automated design encompassed the specifications described previously, to meet the simple functionality required and the associated project budget a lever system was devised (Figure 27a). This lever arm was connected to a pivot point where the test pin would be inserted and rotated. The test pin would rotate from a vertical position through the soil to an angle greater than that witnessed from player boot rotation (roughly 40°). Exceeding these maximum rotations would ensure full assessment of the turf and rootzone to failure – providing a shear stability result. Additional mass could be applied to the top of the lever arm and allowed increased force until failure occurred by pulling the pin through the soil. This allowed the fixed mass of the device to be less, aiding portability but still allowing additional mass to be added; ensuring that pin failure would be achieved. The initial force applied to the pin was important as this assessed the resistance force of the turf and rootzone, the gravity used in the falling lever arm increases the force (shown by Figure 27b). If force applied by the lever arm created movement of the pin, then it was recorded at moments around the pivot, predicting the force on the end of the test pin in the instant before movement occurred. This initial movement was of importance as force increased during the lever arms movement. Therefore, the initial movement was the recorded result as it showed the lowest result to fail the turf. A latch would be incorporated to keep the weighted lever in position and force would be applied on release.

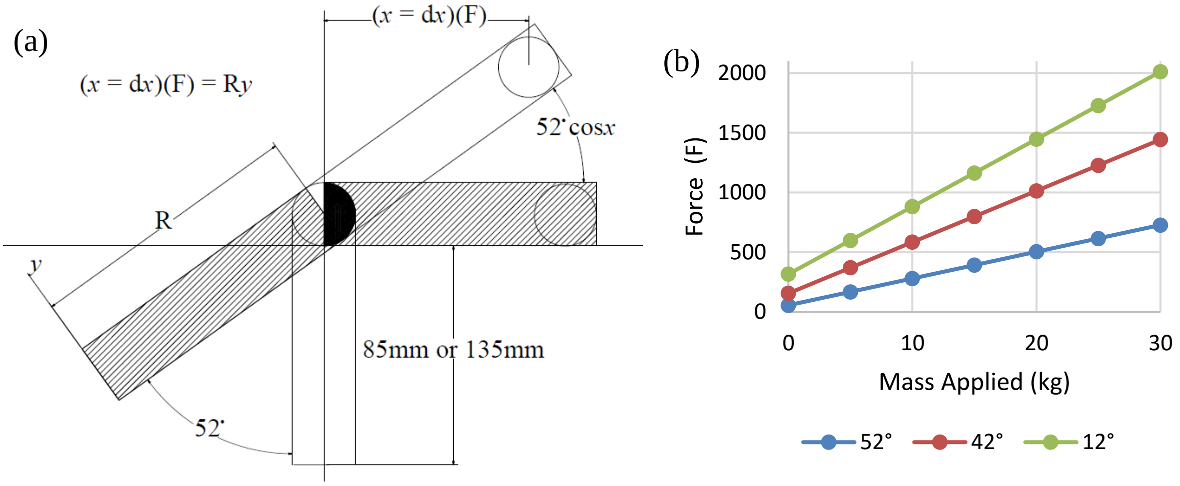


Figure 27 – A concept showing (a) the moments around the pivot point and (b) the effect mass and gravity through the drop angle has on the force results as more mass is applied

- <u>Recording the Force Values</u> – The device result outputs were recorded in two ways. The simplistic method saw the pin forces recorded from the mass applied to the lever arm. This involved using the moments around the pivot to calculate the force applied to the tip of the pin before movement began. The second method used a potentiometer to measure the failure rate, comparing the angle and time. At this initial stage strain gauges were not added (as present on the Going Stick™), because of the absence of known force ranges that the device would produce and therefore strain gauge capacity was unknown. Trialling the device would develop confidence in the results range and would allow more technical instrumentation at higher expense to be incorporated – discussed in Section 4.2.7.

- <u>Effective Measurement of Natural and Hybrid Constructions</u> – Assessment of clay-based pitches was shown to be effective with the potential shear stability testing devices but, they lacked the confinement needed to test sandy soils (Section 3.7) – sandy soils are related more so to surface pressure than water content (Section 3.2.2.2). As higher sand content pitches are common at the elite level, whether in the form of sand-based or hybrid constructions, confinement similar to a player or scrum was required. This was problematic because of the lack of foot data in the scrummage. However, calculated results identified a maximum player-surface pressure of approximately 58 kPa, created from a heavier rugby player's force (120 kg), with an average male UK foot size (UK 10, sole area of 201 cm^2) (Society of Chiropodists & Podiatrists, 2017). This maximum force accounts for full transfer of all their mass through one foot. Equally spreading mass between two feet produces 29 kPa. Although simple calculation dictated target pressures, the device specification and the inclusion of other parts created issues in achieving the pressures required for the plate area in contact with the ground. If the pressure was to be achieved, then the device mass would have needed to be greater, thus limiting transportation. In order to provide confinement but still aid transportation, it was considered that the mass of the operator could be added to the device to create an overall equivalent mass of a larger rugby player (120 kg). However, as the pressures above were calculated maximums and not achieved through previous studies or testing, a footplate area sizably larger than a player's foot area was devised for the device design. This allowed the operator to stand comfortably on the plate. To better evaluate the effects confinement has on sand, a study was undertaken with the device to determine if this property made a large impact on the results produced (Section 4.2.9).

- <u>Fabrication, Materials and Portability</u> – Owing to the high pin forces required to reflect those produced in the rugby scrummage, the materials used needed to be high strength. This informed the technician to use steel and high-strength metals. This would increase the overall weight of the device; however, design features were incorporated to aid movement during testing.

4.2.3 Detailed Design and Equipment Manufacture – Mark I Device

The device detailed, known as the Shear Tester Mark I (MK I), was manufactured from the lever arm conceptual idea. The MK I device (Figure 28) operation utilised a weighted lever arm to transmit a mass through a pivot point to a steel pin inserted into the soil. The weighted test arm mass is increased until the soil failure occurs. The length of the pin can be adjusted to measure stability at several depths up to 100 mm. The operator weight (80 kg throughout the study) when standing on the base plate, provides additional confining pressure to the soil underneath. This device's functionality is described further throughout this section (extracts taken from Paper 2, Section 2).

- The test pins were 20 mm diameter, made of grade 304 stainless steel and fabricated to lengths of 50 mm and 100 mm. These pins were hammered vertically into the soil through the pivot point that kept them in a stable position by means of a grub screw.
- The mass of the device was 32 kg and to increase to the mass of a larger rugby player (110 kg), the operator (80 kg) stood on the device. The design dimensions produce 6 kPa of pressure, which is much less than that calculated in Section 4.2.2. However, at this initial design trial stage, to promote portability and decrease fixed device mass the plate was deemed suitable. Further experimentation investigated the confinement effects of the base plate (Section 4.2.9).

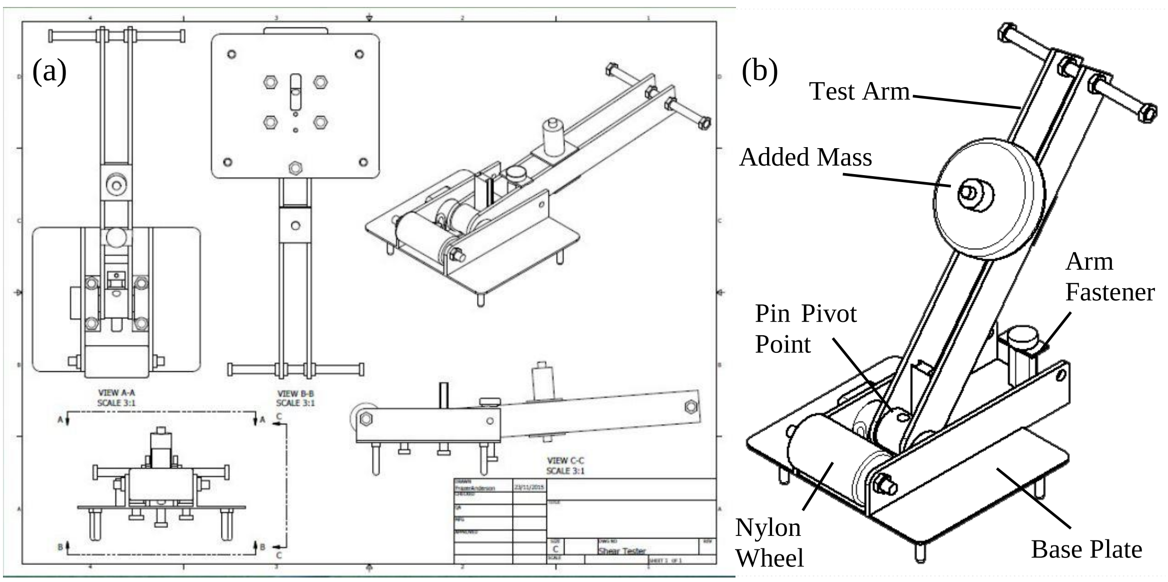


Figure 28 – The Mark I Shear Tester: (a) elevation drawing; (b) design

- The weighted arm created an automated linear movement during the test, which moved through 52° to horizontal (Figure 29). An angle of 52° was used as it allowed greater movement than the specified 27° of a player's resultant force and 40° found visual inspection of turf failures. The main objective was monitoring of the force on the test pin resulting from the initial movement of the lever arm. Rotation of 40° up to full rotation (52°) was typical as the mass increased under gravity during lever movement (seen in Figure 27). Dumbbell weights were added in 5 kg increments until movement occurred. This weight was chosen in order that the test method did not take a lengthy period adding iterations as, after all, the test would finally be established into the Scoreplay™ test with other equipment, with limited time for testing the sports turf/stadia for each.
- A potentiometer (534 Series Pot, 10K, RS Components Ltd. UK) was installed on the pivot to measure the change in angle and time to failure. This potentiometer could not measure the loading or strain effects and was intended to recognise the failure rate of turf in the trail stages. Incorporation and use of strain gauges came with product redevelopment.
- To stop the test arm movement during the addition of extra weights to the device a latch kept the arm secure prior to testing, which, when the (yellow) handle was pulled, released the weighted arm mass through the pin (Figure 29). When the latch was released, the movement was instantaneous and so all the weight of the arm was transferred to the pin. The latch improved the health and safety qualities of the device, decreasing the chance of entrapment by the lever arm dropping unexpectedly. Additional safety was also provided with a (blue) bracket encasing the test area and the falling arm, removing the possibility of mistakenly crushing the operator's feet.
- Portability was increased when the arm was in its locked 'closed' position (horizontal) with a large nylon wheel placed at the front of the device. This allowed the device to be moved easily between locations and in transit to site.

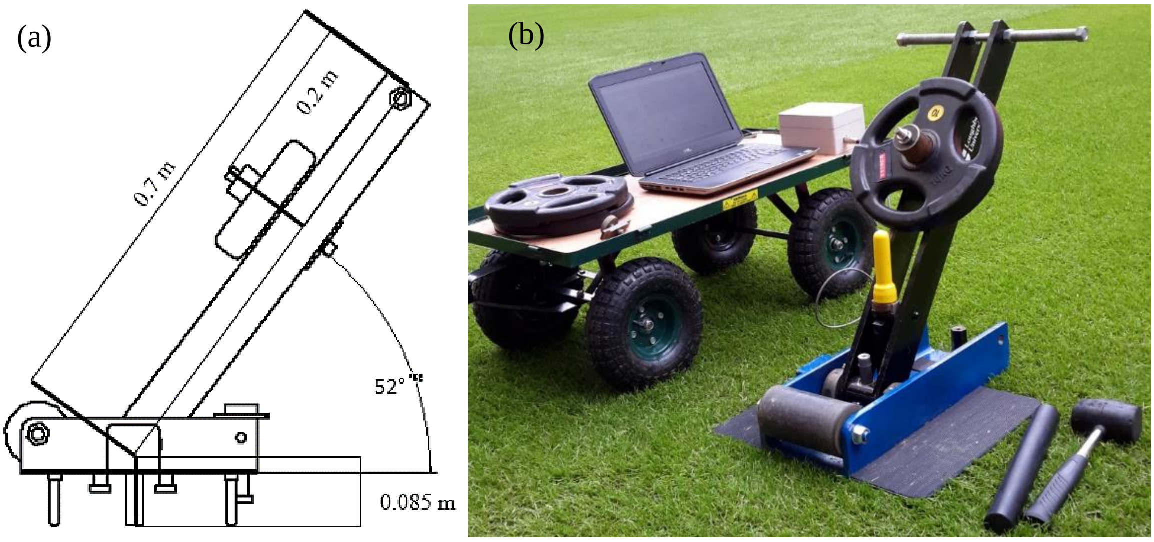


Figure 29 – The Mark I Shear Tester dimensions around the pivot point

4.2.4 TRIAL STUDY – MARK I DEVICE (PAPER 2)

The MK I device was used an untested system different from any other equipment available. Therefore, in order to understand if the device was suitable for shear stability assessment a trial study was undertaken. This employed an empirical scale using differences in weights to determine differences. There were no comparable relationships to other devices and so this paper presented the results of the MK I device, trialled on a range of turf constructions at venues used for the 2015 RWC. During experimentation it was expected these venues would be high quality as Scoreplay™ had been utilised some months previously. During the trial study of the MK I data collection, the Scoreplay™ tests were also used, detailing full agronomic classifications and a suite of industry standard player performance tests. The combined data from 13 of the venues of a variety of constructions provided a useful data set to evaluate, benchmark and refine the Shear Tester, providing validity of its conceptual design.

The findings of Paper 2 (Sections 4 and 5) show that the MK I shear tester could assess high pitch shear stability to a shallow depth with a 50 mm pin and the low shear stability at deeper depth with the 100 mm pin. This was because the device arm mass was too heavy to measure the most sensitive results created by the 50 mm pin and for the 100 mm pin it was not possible to place enough 5 kg weights on the arm to provide movement. The MK I device's relationship to other Scoreplay™ tests showed evidence of a relationship to the CIH and RTD, albeit weak, and it was concluded that the device was assessing a characteristic of the sport turf not currently measured by standard industry tests. The Shear Tester differentiated between the high stability of the hybrid pitch constructions and the weaker natural pitches. A scale compared the Scoreplay™ percentile quality rankings with the Shear Tester results, indicating a few pitches with high Scoreplay™ rankings that had poorer shear stability results.

The outcomes identified that the device correctly investigated an unmeasured property when it was mapped against other Scoreplay™ performance tests, albeit to fully assess the limits of modern sports turf the available force range needed to increase sensitivity for the 50 mm pin and to produce greater forces for the 100 mm pin (Paper 2, Section 5). Redesign of the device would address this issue to allow assessment of a full range in turf quality. The foot plate was seen to provide enough confinement to show differences between sandy soils with and without hybrid constructions included.

The main undertaking of the project was to develop a test that measures shear stability to depth. The need for the stability test (discussed in Section 1.3.1) is clear from the results as on rare occasion the Scoreplay™ quality percentile, score, indicating 'good' conditions did not align with the shear stability performance (Paper 2, Section 3). During the test in question, the surface performance was adequate, however, high sand content and shallow grass rooting affected the shear stability but showed positive results for other performance and agronomic tests. It is in this case that the device is required to provide a more representative Scoreplay™ rank for this suite of tests, however, the majority of the time Scoreplay™ is a useful indication of good and bad quality pitches produced from the other performance results.

4.2.5 TEST REDEVELOPMENT – MARK II DEVICE

Paper 2's trial study identified that the MK I required modification to include a greater detectable stability range of forces for both pins. This would provide more sensitive readings for the 50 mm pin and, moreover, apply greater force to achieve the maximum 100 mm pin readings.

After consideration of the MK I design and the specifications, the device was redesigned with input from the technician in order to meet the requirements to keep the design simple, remain portable and be cost-effective. The simplest method was to add a cantilever beam onto the existing arm (Figure 30). The cantilever (9.25 kg) could either be folded up into the main test arm (17.24 kg) to add to the weight so that larger forces can be applied to the test pin or be extended to create a counter force on the main test arm. Additional mass (5 kg weights) could be applied on both the cantilever and main arm, offering more variety and decreased 'step' forces applied to the pin. Apart from the addition of this cantilever altering moments around the pivot point, the device operation for the MK II device did not change from the MK I.

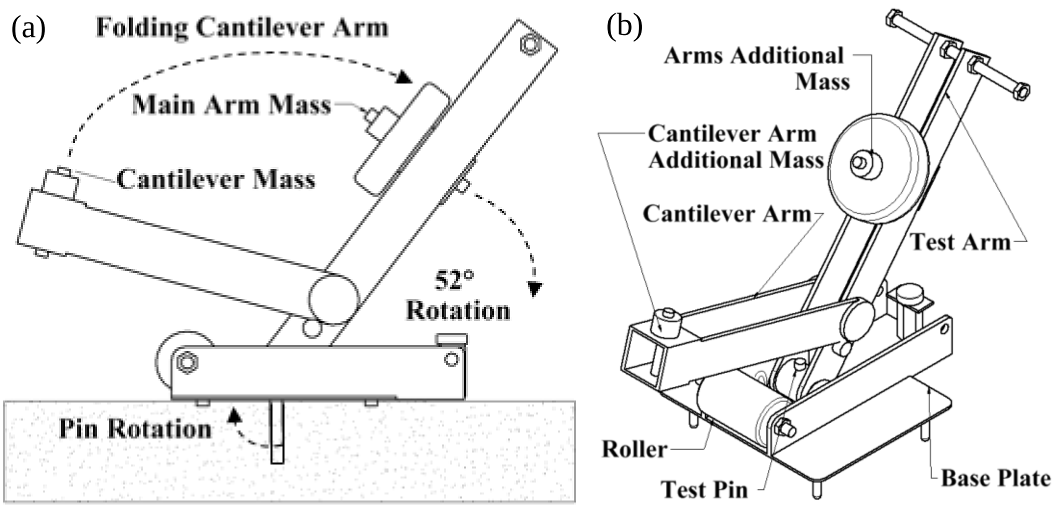


Figure 30 – Schematic of the Mark II Shear Tester showing the cantilever positioning. (a) Shows the arm that can be left in place or folded inwards creating greater mass on the test arm;(b) shows a labelled schematic of device parts

This method proved useful in the initial movement, however, as more of the cantilever passes over the pivot point, there is an increased force working against the pin. The increased mass of the cantilever on the MK II device also produced larger confinement on the plate creating a pressure of 7 MPa at 120 kg when the operator stands on the base plate.

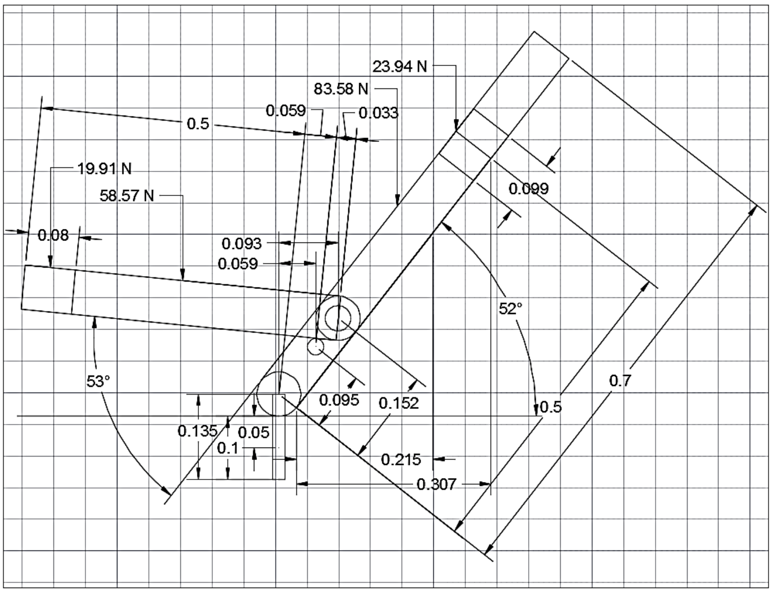


Figure 31 – **Moments about pivot point for Mark II cantilever design**

Table 8 shows the calculated maximum initial force on the tip of the pin (deepest point) using moments about the pivot for a range of masses added to the test arm and cantilever arm when it was vertically inserted into the soil (shown in Figure 31). However, the 'moment' maximum force estimated here is not a precise value from the turf shear strength as a consequence of the method. For example, for a mass of 10 kg on the test arm, the turf may be stable but for a 15 kg mass, the soil may readily fail, such that the specific yield force is somewhere in-between. Clearly, one refinement is to have many small increments of mass available. For operational simplicity and transport, and based on early field trials which established broad classes of high, medium and low turf stability (Paper 2, Section 4), 5 kg increments of mass applied to the main arm and/or the cantilever arm was deemed acceptable.

In Table 8 when the cantilever is in use, the two masses are separated by a colon (i.e. 5:5 or 10:5), where the first number indicates the mass on the test arm. For the 50 mm pin, the range of forces that can be measured by the device is 187 N to 2.1 kN, and for the 100 mm pin the range is 117 N to 1.1 kN, respectively.

Table 8 – The range and increments of pin forces achievable for masses applied to the arm(s), showing step changes for the 50 mm and 100 mm pins

Mass Applied (kg)		5:5	0	10:5	5	10	15	20	25	30
50 mm Pin	+ Cantilever (N)	187	235	375.	424	612	800	1177	1365	1554
	Test arm Only (N)	x	x	704	1059	1237	1414	1770	1947	2125
100 mm Pin	+ Cantilever (N)	117	148	236	267	385	622	741	859	978
	Test arm Only(N)	x	x	443	555	667	778	890	1002	1114

4.2.6 VALIDATION STUDY – MARK II DEVICE (PAPER 3)

Product validation was undertaken in the laboratory on a variety of controlled soil samples, and during a field study (see Section 2.3.3 and Paper 3, Section 3). In the laboratory, the device measurements were shown to be sensitive to the shear strength of a high clay content soil. This was evident as when the water content was increased, or the density was less than the shear stability of the soil texture decreased. This corresponds to the expected properties for clay as stated in Section 3.2.1 and Paper 3, Section 5, where strength decreases with increasing water content or decreasing density. The sandy soil’s shear was unaffected by changes in water content, as predicted and detailed Section 3.2.1. The sandy soil’s 50 mm pin results are not as sensitive to the soil state as those of the 100 mm. The Fibresand™ reinforced rootzone soil, with PP fibres present throughout, showed improved shear resistance compared with the sandy soils. A programme of field data produced from high-quality pitches used for the RWC suggested a large effect was supplied from the turf root reinforcement. Sandy laboratory samples gave lower shear stability readings by a factor of around two or greater, in broad agreement with previous research on the added benefit of the reinforcing effects of grass roots (Paper 3, Section 5.1). A conceptual model (Paper 3, Section 5.2) of soil failure with the pin, discussed further in Section 4.2.9, was developed to identify the key soil variables and support experimental data interpretation, based on review of the material's visual failure zones. For the laboratory sandy soils, the size of differences observed was similar to that expected using simple soil mechanics theory. However, the size of difference from experimental data was lower than that predicted from the simple model, which predicted a factor of up to three (Paper 3, Section 5.1).

Outcomes indicated that the MK II device force range was more appropriate when measuring with the 100 mm pin, showing differences between the materials, but the 50 mm pin still could not measure the most sensitive of sands. The lowest force available with the 50 mm pin was a negligible 187 N (Table 8); thus, instead of the force being the issue, the low confinement of the plate may have a greater influence. This is apparent as *in-situ* testing provided useful results for the 50 mm pin as it could detect shear strength provided by grass rooting or hybrid additives. Moreover, the MK II device measures in force steps creating a range. Although useful in determining a rough understanding of shear stability, the device could benefit from greater force sensitivity. Therefore, to understand the soil texture failure as the pin pulls through, the device could incorporate recording the physical results instead of the moment force on the pin. This would provide results for the materials' failure curve and further benefit the conceptual shear model by providing results that might find a closer relationship to the calculations.

Therefore, further development of the device would incorporate a method to measure the pin's physical resistance as it pulls through the angle. Investigation would examine plate confinement to determine the effects of increased pressure on sandy soils. Moreover, review of the conceptual model against the new device results offer device refinement suggestions if required.

4.2.7 DESIGN DEVELOPMENT AND MANUFACTURE – THE HAND PULL SHEAR TESTER

The outcomes of Paper 3 detailed that parts needed incorporated to accurately assess the physical force and torque placed on the pin. This proved problematic for the technician to fabricate on the MK II. Therefore, a new device, the Hand Pull (HP) Shear Tester (Figure 32), was designed and manufactured, to identify specifically to test this physical force/torque parameter. As the HP design, although using the same pin method for testing, the mechanism was radically different from the MK II device, the two were compared to ensure that their results were similar (see Section 4.2.10).

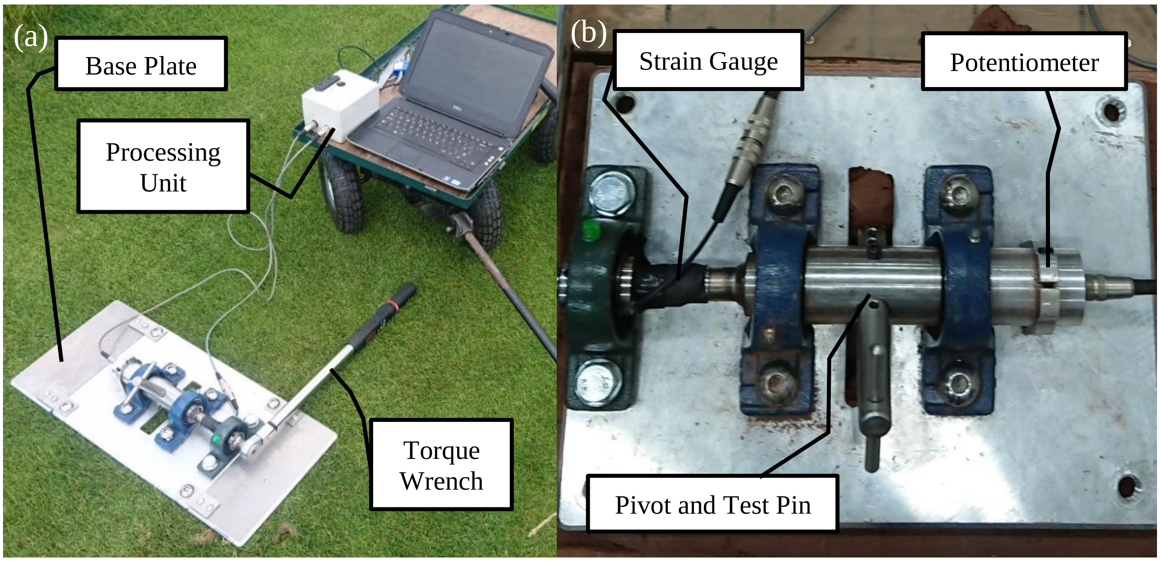


Figure 32 – (a) Side view of the Hand Pull device. (b) The elevated view

The HP Shear Tester's main difference was the pin mechanism to pull it through the turf. The operator still stood on a base plate, but movement occurred when the operator pulled a torque wrench connected to the pivot, which pushed the pin through an angle (roughly 45°) in the average time the MK II device takes to reach failure (1–2 seconds) (see Section 4.2.8). As the device was pulled by hand there was no way to maintain the loading rate for each time and so repeatability was affected; however, by ensuring time to pull the device was 2 seconds this would reduce discrepancies in results. When the torque wrench was pulled, moving the pin, a bespoke strain gauge and potentiometer (534 Series Pot, 10K, RS Components Ltd., UK) recorded the torque and angle values, respectively, against time, providing a greater indication of the failure of the turf construction. The peak torque of any curve taken within the first 40° was taken as the shear stability result. The torque values were then readily converted into force with the moments around the pivot so that they could offer comparison to the MK II results.

Although the HP did not offer the same level of repeatability in the test method as the MK II device, this design was evaluated as the best way to meet the majority of the original specifications proposed by Labosport (Section 4.2.1). Encompassing these specifications saw improvements in portability, reducing the device to 11 kg (aluminium base). This was made possible by the reliance on the operator to apply force to the pin opposed to the weighted lever arm. The base plate was smaller but still offered the same confining pressure as the MK II (7 kPa) when the operator stood on the plate. This was chosen to offer direct relationship to the MK II in the analysis of subsequent studies results. If the plate was to meet the rugby player foot pressure of 59 kPa (detailed in Section 4.2.2), the device mass would increase, reducing portability. Furthermore, the calculated torque values in operation would be unachievable with the operator's input (calculated to require more than 300 Nm). To further explore confinement changes on the test device results and their relationships, they were applied to a study investigating higher confinement on sand material (see Section 4.2.9).

4.2.8 DETERMINING THE RATE OF SOIL FAILURE

The MK II device used a potentiometer which measured angle and time of failure (discussed in Paper 2, Section 2.1 and 3.1). This distinguished differences in turf that failed at the same magnitude of mass applied to the device arm. The rate of failure for the MK II device is determined by the shear stability of the soil as the arm falls with gravity. This was useful to a certain extent, showing the difference between a 'slow' failure and a 'fast' failure (Figure 33), and helped to indicate if the mass applied to the device was near that of the actual turf failure threshold (indicated with a slower failure curve). However, the resolution of the MK II force results, applying the increasing 5 kg steps, provided a ‘force range’ instead of the turf/rootzones’ true failure force (Paper 3, Section 2.2 and Section 4.2.6). Therefore, to provide greater resolution of the soil’s resistance at failure the HP device was validated similarly to the MK II device. Exploring the outcomes produced by of Paper 3 saw the HP device used in further laboratory studies and the grass plant establishment study.

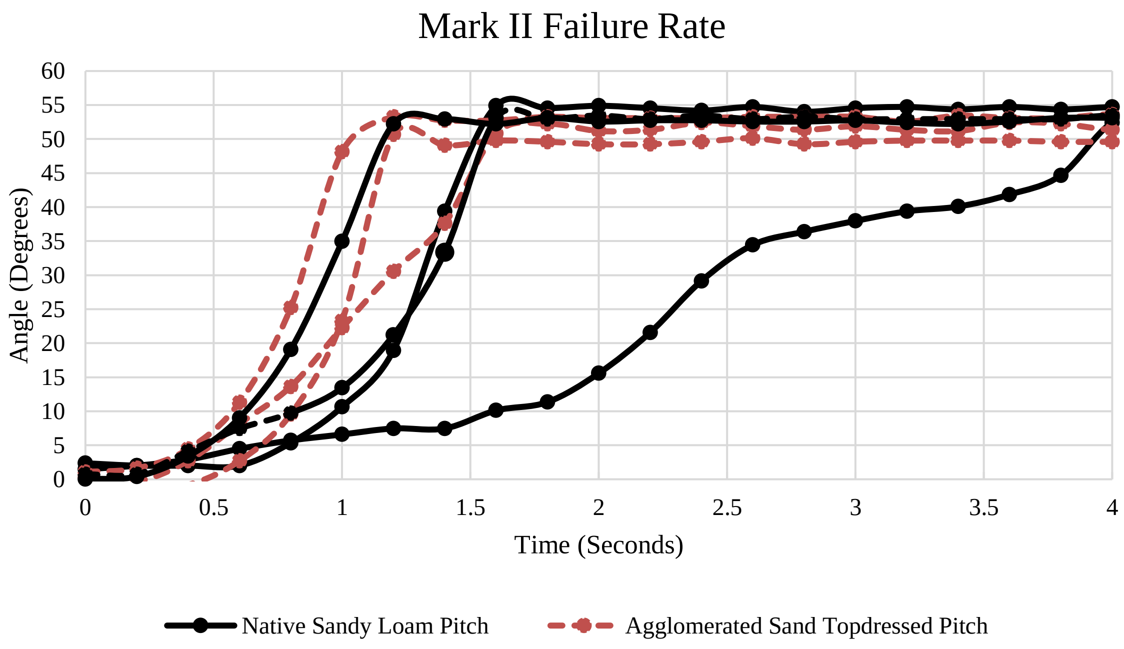


Figure 33 – Mark II potentiometer readings showing variation in failure from a 50 mm pin and 5 kg applied mass

The initial laboratory study validation for the HP device used a Fireclay (58 % clay, 31 % sand, 11 % silt), routinely used for research (Paper 3, Section 3) at known water content and density. The simple Hand Shear Vane (Section 3.6.2), a test used routinely in geotechnical study, was used to offer a suitable approximate measure of clay shear strength results and was considered sufficient in comparing to the HP device findings through its continued common use and British standardisation.

Figure 34 shows the Shear Vane strengths of 240 kPa, 131 kPa and 62 kPa produced at a common range of clay rootzone gravimetric water content of 14 %, 17 % and 20 % respectively. The HP device results show the minimum and maximum torque value produced from six samples at each water content. Both the Shear Vane and the HP device shows increasing strength/torque results as water decreased. However, the HP device's highest recorded values (in the first 20°) showed that factor of change decreases as the torque further increased. The Shear Vane results showed an increase by a consistent factor of roughly 2. Additional analysis of the HP device showed as the water content increases, the mode of failure changes – to expected mechanical principles of clay shown in the stress strain curve in Section 3.2.1. The 14 % water content displayed greater torque, a brittle failure and a defined peak point was reached before it reduced in torque. The 20 % water content displayed low failure and a plastic yield with torque increasing fractionally with movement. In this case, it does not reach an ultimate strength and could be a result from the highly water saturated clay. The 17% has a curve more similar to that suggested in Figure 9 properties, reaching an ultimate stress before decreasing.

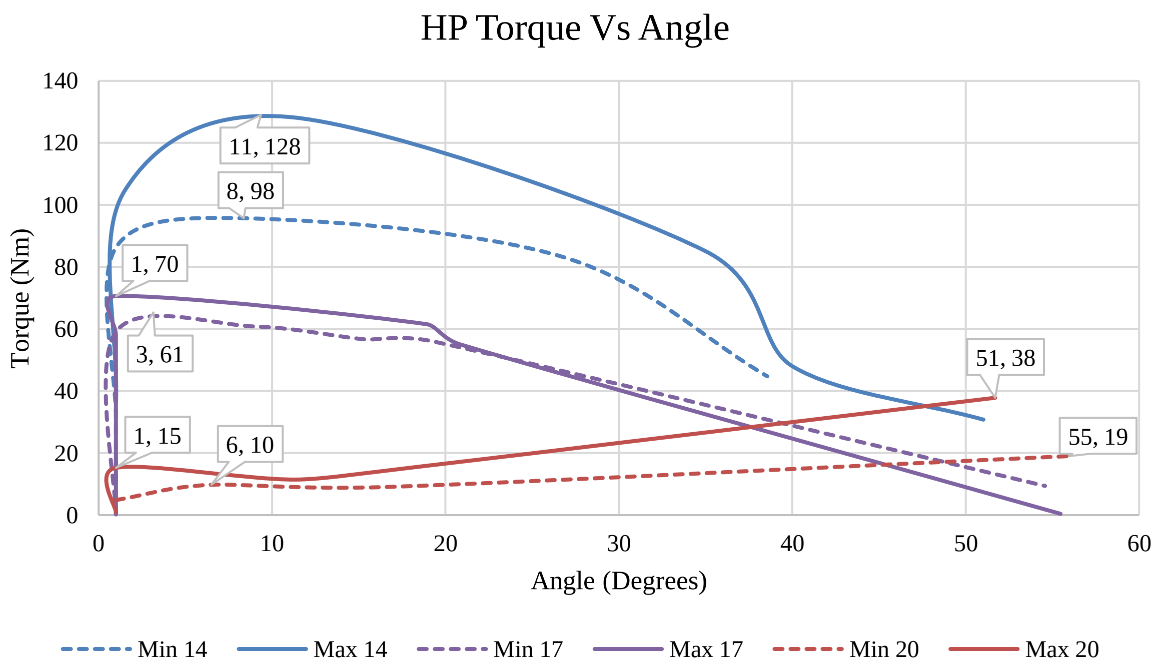


Figure 34 – The torque values for the 50 mm pin as it pulls through the Fireclay at 14 (240 kPa), 17 (131 kPa) and 20 % (62 kPa) gravimetric water content

The outcomes suggest the HP device monitored the behaviours of the Fireclay and showed differences in shear strength, as would be expected with increased water content, defined in Section 3.2.1. However, the test also confirmed that the HP device results did not increase at the same factor as the Shear Vane results, which may in part be due to the repeatability of the HP method. This fact is demonstrated by the large range between the maximum and minimum torque at 14 % water content.

4.2.9 ASSESSING PLATE CONFINEMENT AND THE CONCEPTUAL MODEL

Section 3.2.2.2 details the mechanical properties of sand under confining pressure. When sand is compressed the frictional forces and angle of flexion (friction) increases making the sand stronger. The 7 kPa of the base plate was low compared with the calculated rugby foot pressures (Section 4.2.2). Therefore, in order to investigate confinement and effectiveness of the base plate, a laboratory study was conducted whereby the confining pressure on the base plate was increased. The conceptual model (discussed in Paper 3, Section 2.2) was applied to findings of the study to identify whether it produced similar outcomes to Paper 3 (Section 4.2.6). The model was then evaluated both with sand and clay rootzone materials to suggest causes for the discrepancy between calculated and physical results.

Prior to testing with the Shear Tester, shear box testing, which measures granular material’s strength properties under confinement, was undertaken on common rootzone sands. Table 9 presents the results of shear box testing for MM45 (fine 11 %, medium 84 %, coarse 5 %) and Fibresand™ (fine 17 %, medium 67 %, coarse 26 %) samples (discussed in Paper 3, Section 5.1). Tests were carried out at several confining pressures, two dry densities and two gravimetric water contents. The density and water contents represented a minimum and maximum range found from the data base of *in-situ* pitch testing. The results show the variation in average peak angle of friction (φ') that can be derived for any one material due to the change in initial state and applied confining stress. In general, water content showed little effect;

however, increases in density showed an effect of increasing the angle of friction, by around 5–6° for the Fibresand™, which also displayed larger magnitude values than the MM45 due to the fibre reinforcement effects.

Table 9 –MM45 and Fibresand™ angles of friction derived from analysis of shear box testing at two gravimetric water contents, and two bulk densities.

	Gravimetric Water Content (%)	8	17.5	8	17.5
	Dry Density (g/cm^3)	1.2	1.2	1.6	1.6
Fibresand™	φ′ average	44	44	47	50
	φ′ at 10 kPa	50	50	58	58
	φ′ at 50 kPa	43	43	46	49
MM45	φ′ average	39	37	39	41
	φ′ at 10 kPa	42	46	45	48
	φ′ at 50 kPa	39	37	38	41

The laboratory-based method developed allowed a controlled level of confinement to be applied to the Shear Tester base plate (MK II and HP devices), as shown in Figure 35. Steel beams represented the operator's mass on the base plate (80 kg). A pneumatic jack and a proving ring provided measurement and increased pressure on the base plate to reach greater confinement stress (further apparatus detailed in Appendix F). The sand material, an '80/20' (fine 8 %, medium 69 %, coarse 23 %), was placed into the box in layers at a controlled density of 1.4 g/cm^3 to replicate the average provided from field testing. Three confining pressures were then applied before the Shear Tester readings were taken: at 7 kPa, representing the current device's confinement with the operator; at 50 kPa, representing the estimated maximum vertical stress under a single boot of a rugby player; and at 100 kPa to extend the range for further analysis.

Table 10 details the average maximum 50 mm pin force results of the MK II and HP devices provided by six samples at each confining pressure. These were calculated from the moments (MK II) and the maximum torque within the 40° angle, converted to force. The results show increasing peak pin force with increased confinement for both devices (comparison of devices is discussed in the next section).

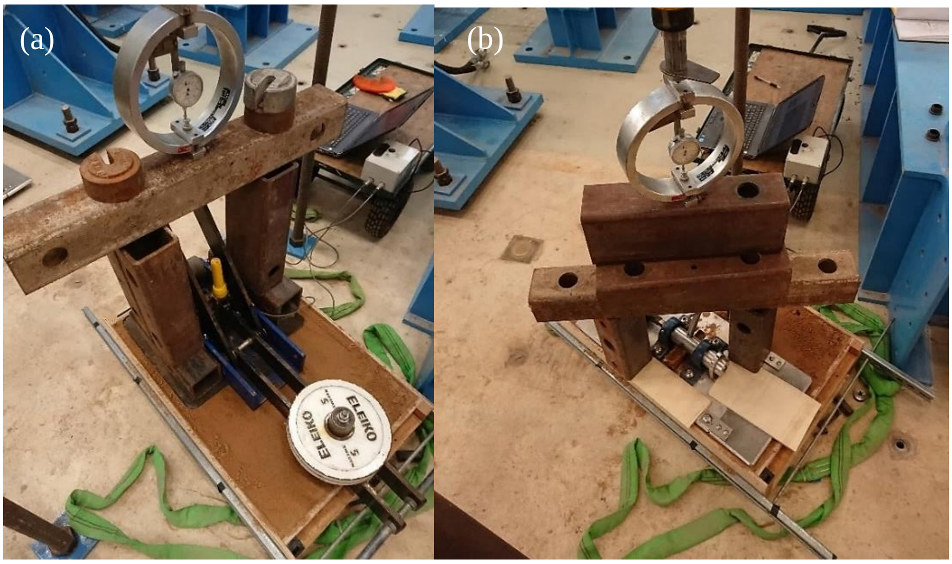


Figure 35 – (a) The Mark II device and (b) Hand Pull devices under high confining pressure using the steel beams. The jack was applied to further increase pressure on the plate.

Table 10 – Mark II and Hand Pull Shear Tester results at the two confining pressures

Device	Confining Pressure	Average Maximum Pin Force (N)
MK II (50 mm pin)	7	187
	50	235
	100	424
HP Shear Tester (50 mm pin)	7	165
	50	241
	100	426

Figure 36 shows the resistance increase (torque) on the pin for the three confining pressures recorded for the HP device. The results show a difference in their failure as suggested by soil mechanics literature (Barnes, 2010) and stated in Section 3.2.1. The higher confinement increases the peak torque values. The highly confined 100 kPa result could be suggested to be brittle failure tailing off after reaching a peak. The 50 kPa result is more ductile-brittle with a reduced but smoother increase in the torque curve with a smaller decrease. The 7 kPa result appears to offer little confinement and as consequence the torque values are low. This may suggest that when the shear tester is used on an *in-situ* high sand content pitch that the pin is effectively measuring grass/composite strength opposed to any strength produced by the sand.

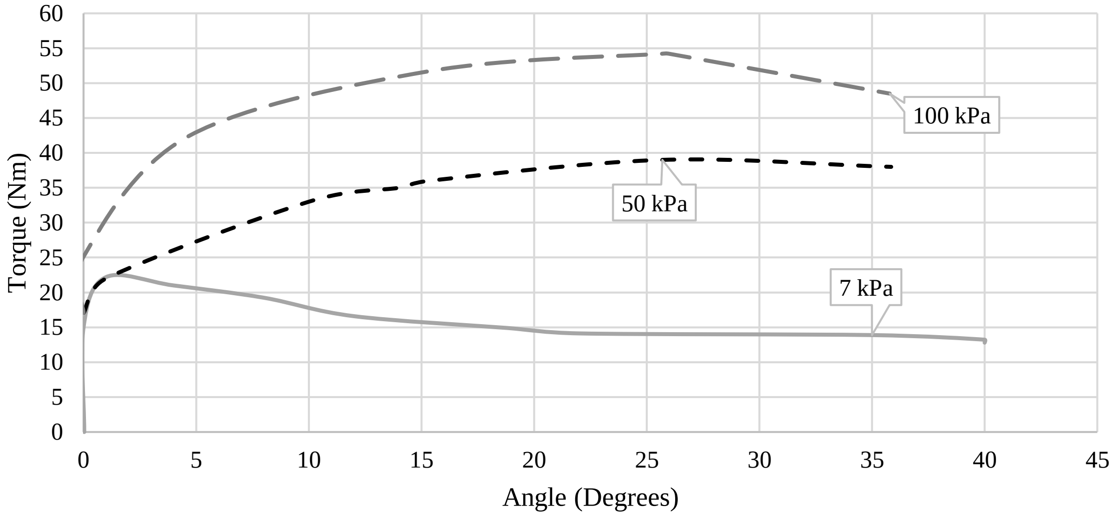


Figure 36 – A graph showing pin torque versus angle of rotation for three confining pressures

The results for the experimental tests in Table 10 were compared with the predicted failure forces from the conceptual model. The predicted model results observed from the experiments, produced similar outcomes to Paper 3, whereby the model shows great sensitivity to the magnitude of the earth pressure coefficient (K) that is selected (and which is unknown) (Paper 3 Section 2.2 and 5.1). If Kp (passive coefficient of earth pressure) was selected the model overestimates the observed peak force at failure, and if Ko (earth pressure coefficient at rest) is selected the model underestimates the observed peak force at failure. Further investigating K, Table 11 shows the results for when K was set such that at 7 kPa confining pressure the predicted failure force was equal to that observed. It shows that for the predictions at confining pressures of 50 kPa and 100 kPa there was still approximately a factor of four times the difference between the predicted and observed forces. This indicates that either the conceptual model may need refinement to better represent the rootzone failure mechanism, or that the confinement applied does not have the effect expected, perhaps because of the gap in the bearing plate.

Table 11 – Predicted pin failure forces for sandy soils using a simple soil failure model

Plate Pressure (kPa)	Soil density (g/cm^3)	φ’ (°)	Predicted Pin Failure Forces (N) for K	Observed Pin Failure Force (N)
7	1.4	45	165	165
50	1.4	39	913	241
100	1.4	39	1819	426

The conceptual model was further evaluated for clay material. Paper 3, Section 4.2 discussed that the densities, especially at high water content values were low compared with their maximum full-face compaction (highest achievable density) and may have provided a reason why the conceptual model greatly overpredicted peak force. Repeat laboratory testing, similar to that in Paper 3, Section 3, was undertaken but with increased Fireclay density. Table 12 shows these increases in density, the results for the MK II device for Paper 3 and the repeat testing (MK II and HP device), comparing them against the Shear Vane and calculated predicted peak force results. The findings showed that despite the increases in density, mainly in the wetter Fireclay, the conceptual model still produced greater predicted results than observed values, albeit now to a smaller factor (one-third greater).

Table 12 – Calculated clay actual and predicted peak force of samples

	w/c (%)	Density (g/cm^3)	Air Voids (%)	Shear Vane (kPa)	MK II Peak Force (N)	HP Peak Force (N)	Predicted Peak Force (N)
Paper 3	14	1.83	4	238	675	n/a	1309
	17	1.42	21	145	376	n/a	798
	21	1.11	36	63	187	n/a	347
Repeat Test	14	1.83	4	240	1052	821	1320
	17	1.79	5	131	424	497	721
	21	1.62	7	62	235	262	341

Outcomes produced from investigating the confinement of the plate indicate that the plate produces some confinement to the sand surface when at the pressure expected under a player’s boot (50 kPa). Unfortunately, 7 kPa seems too low to have a large effect on the sand confinement, however, it can be effective in measuring the strength that is provided by grass rooting and hybrid systems. The 50 kPa results suggest that it is possible for the operator to pull the HP device using this higher pressure, providing more relatability to player boot pressures.

However, it must be considered that weaker bare rootzones were used and it is unknown how much grass and synthetics would increase the strength. This would require trials so as not to create a device with unachievable forces/torques required to pull the handle. When comparing the results of the conceptual model for sand and clay, the model overpredicted the pin failure force for both materials. Even when the model predicted output was set to the observed force at 7 kPa, the other predicted forces were far greater for the other values (50 kPa and 100 kPa). Clay materials did see some improvement in similarities between the predicted and actual force comparisons when density was increased, showing increases in strength with increased density and decreased air voids. In order to improve the conceptual model, it needs to be refined to assume that partially saturated soils are used instead of the fully saturated soils currently used. It should also include the influence of voids and other variables that can be witnessed in common rootzones used in turfgrass sports pitches.

4.2.10 FORCE RELATIONSHIPS BETWEEN THE MK II AND HAND PULL SHEAR TESTER

In order to ensure that the MK II and HP devices produced equivalent force results, the devices were compared with laboratory-controlled experimentation. Figure 37 shows Fireclay results at different water content values and their repeat testing (indicated by brackets). Results were similar for both the MK II and the HP devices. The variations between the two devices results were attributed to the resolution of the MK II device (see Section 4.2.6).

Figure 38 shows the 80/20 sand samples at varying confinement and water content. The device results were again similar, with more closely related results than the clay. The lower forces produced smaller results steps that could account for the greater sensitivity of the MK II device at these force values.

These results meet the outcome of Paper 3, Section 6, proving that the HP device produces a more accurate assessment of soil shear stability and determined a more conclusive failure curve of soil textures, even at low strength. The closeness of the results obtained for the HP and the MK II indicates that data produced from either device in further testing can evaluate the constructions similarly.

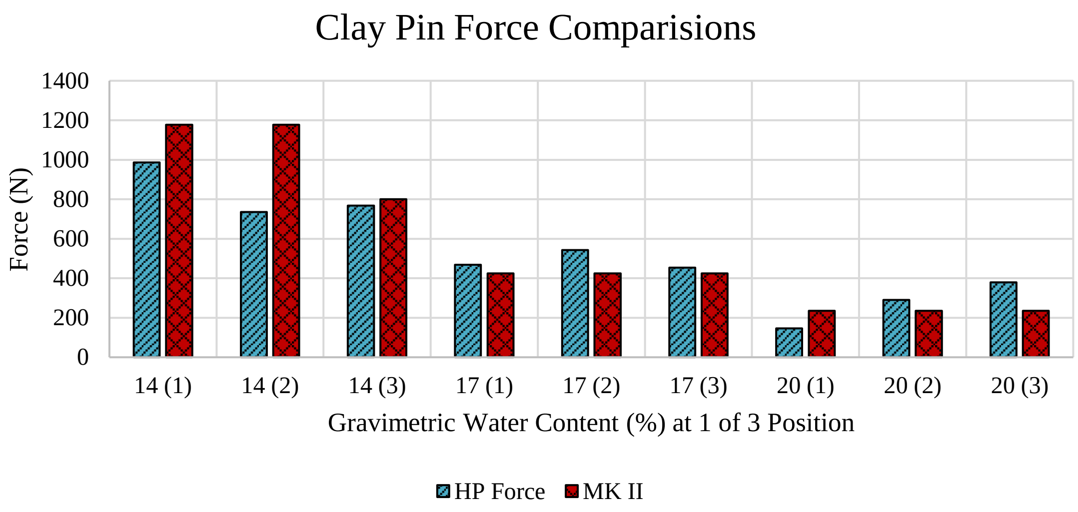


Figure 37 – Comparison of the clay Mark II results and the Hand Pull results

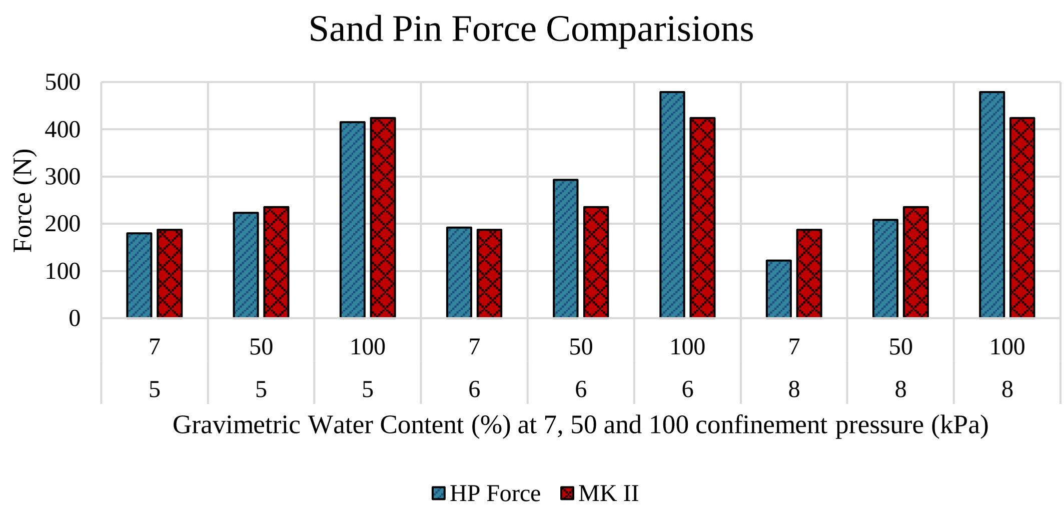


Figure 38 – Comparison of the sand Mark II and the Hand Pull results

4.3 INVESTIGATING VARIABLES AFFECTING TURF SHEAR STABILITY

The research literature found shear instability of sports turf to be influenced by water content, density, grass plant establishment and turf construction/texture. The laboratory validation had already assessed some of these variables. However, there were two further experimental research projects undertaken to explore the effects of turfgrass and turf construction in the Grass Plant Establishment study and water content in the Soil Water Content study. This section presents the results of those studies with discussion and analysis presented in Section 5.

The MK II was used for the majority of testing; however, to provide physical failure readings the HP device was utilised to measure mature grass in the Grass Plant Establishment study.

4.3.1 GRASS PLANT ESTABLISHMENT STUDY

The study (referred to in Section 2.3.3 and Appendix G) was created to monitor the effects of seeded perennial ryegrass growth in six different common natural and hybrid constructions over a period of 18 months. The constructions were a native loamy sand soil, 80/20 sand, Fibresand™ and three carpeted systems (Mixto s.r.l. Mixto™ and The Motz Group© Eclipse™ and Hero™). Figure 39 shows the six plot constructions increasing in grass establishment and coverage over the test period from the initial seeding. The greatest increases were seen in the first 5 months with more gradual growth afterwards. The decrease in coverage mid-July was caused by loose soil movement by wind, covering the grass plant and reducing root establishment and coverage.

The important agronomic variables were examined using statistical analysis (Appendix I) to determine correlation and regression produced between them and the Shear Tester force results for the 50 mm and 100 mm pins. The HP device results were used to analyse the turfgrasses shear stability at different water contents during maturity.

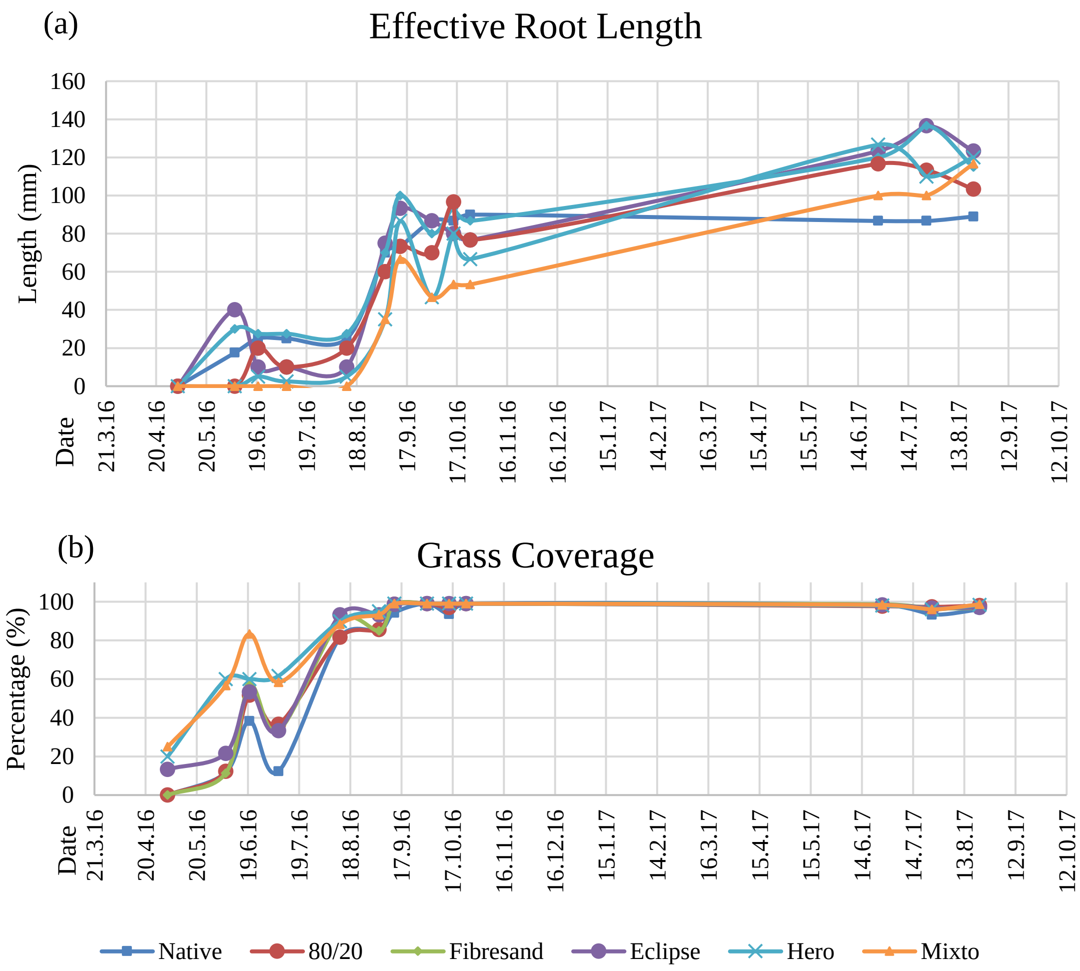


Figure 39 – (a) Grass rooting and (b) coverage during the grass establishment study

4.3.1.1 Soil Core Properties and Environmental Conditions

The study constraints (Section 2.4) detailed that because the testing was being subjected to the outdoor environment not all conditions were controlled. Therefore, to account for the possible range of different test conditions, Table 13 shows the data spread of the recorded results for all the test sessions.

Core samples taken during each test visit provided gravimetric water content, bulk and dry density of the turf. The water content values varied throughout the study, owing to rainfall and temperature, as the grass established into the constructions. Both gravimetric and volumetric readings were taken. The volumetric water content readings were collected with a TDR probe

(ML3 ThetaProbe Soil Moisture Sensor, Delta-T Devices Ltd, Cambridge, UK). Dry density and air voids remained similar throughout the test period.

Table 13 – Environmental data and calculated gravimetric water content, bulk and dry densities and air voids collected from cores on site during the 13 tests

	Native	80/20	Fibresand™	Eclipse™	Hero™	Mixto™
Gravimetric Water Content (%)						
Min	9.91	5.62	5.18	5.67	5.78	6.14
Max	21.71	25.34	25.10	26.37	27.72	28.22
Mean	15.01	12.95	13.67	15.08	12.97	15.49
Standard Deviation (2 DP)	3.80	7.33	6.41	6.88	7.17	7.74
Bulk Density (g/cm^3)						
Min	1.27	1.26	1.24	1.20	1.22	1.12
Max	1.61	1.79	1.51	1.64	1.57	1.52
Mean	1.44	1.42	1.41	1.38	1.38	1.39
Standard Deviation (2 DP)	0.10	0.15	0.08	0.13	0.12	0.11
Dry Density (g/cm^3)						
Min	1.13	1.15	1.12	1.10	1.15	1.01
Max	1.40	1.45	1.34	1.32	1.32	1.36
Mean	1.25	1.26	1.23	1.20	1.22	1.22
Standard Deviation (2 DP)	0.08	0.10	0.08	0.08	0.05	0.10
Soil Air Voids (% 1 DP)						
Min	26.3	9.4	25.2	18.2	22.7	27.0
Max	45.5	47.7	52.5	50.4	49.7	50.1
Mean	36.3	35.8	36.8	35.9	37.4	37.8
Standard Deviation (2 DP)	5.43	10.95	8.21	9.60	9.32	7.50

	Test Temperature (°C)	Monthly Rainfall (mm)	Test Humidity (%)
Min	4	27.90	43
Max	31	83.60	96
Mean	16	44.22	73
Standard Deviation (2 DP)	4.41	21.87	9.23

4.3.1.2 MK II Shear Tester Calculated Force Values

Table 14 details the results produced by the MK II Shear Tester, split between an initial period (5 months) where there was minimal grass/root establishment and the period where grass rooting/plant started to establish.

The results from the 50 mm pin showed an increase in force values as the grass established in the construction plots. The 80/20 material had the weakest values at all stages through the testing followed by the Fibresand™ and the native plot. The native turf gained strength in the established grass period. The carpeted hybrid systems began with the highest initial force values and increased in strength as the grass established. The greatest force was found with Eclipse™ followed by the Mixto™.

Table 14 – Mark II Shear Tester 50 mm and 100 mm pin results for the different construction types over the study, separated into the early stages (first 5 months) and after

	Native	80/20	Fibresand™	Eclipse™	Hero™	Mixto™
50 mm Pin Force: Initial 5 Months (N)						
Min	236	187	187	376	236	187
Max	376	376	424	707	613	613
Mean	329	266	332	486	416	400
Standard Deviation (2 DP)	72.07	87.41	95.97	139.11	120.74	180.96
50 mm Pin Force: After 5Months (N)						
Min	400	306	376	596	376	424
Max	738	613	706	1061	613	706
Mean	550	431	488	732	529	585
Standard Deviation (2 DP)	139.77	109.57	134.66	163.72	106.45	114.99
100 mm Pin Force: Initial 5 Months (N)						
Min	766	443	443	443	443	443
Max	1181	443	707	825	825	707
Mean	1005	443	565	704	645	610
Standard Deviation (2 DP)	150.67	0	135.11	135.57	135.48	97.68
100 mm Pin Force: After 5 Months (N)						
Min	707	588	588	707	516	588
Max	1299	1062	1062	1062	944	1062
Mean	1011	695	783	856	741	808
Standard Deviation (2 DP)	182.48	170.3	184.81	126.96	137.75	173.55

The 100 mm pin showed similarly that the 80/20 was the weakest throughout the study. The Fibresand™ values were comparable to the carpeted hybrid plots when grass root/coverage established. The Eclipse™ still produced, on average, the greatest forces of the hybrid constructions, however, the other carpeted constructions were more similar to each other than to the 50 mm pin results. The native plot produced the highest forces overall with small increases in force as the grass established in the plot.

4.3.1.3 Shear Tester Correlation and Regression Values

The values produced with the MK II Shear Tester 50 mm and 100 mm pins were compared for the agronomic values (plant growth/rooting, water content and soil conditions) of the six constructions over the entire test period. These variables were input into SPSS comparing single relationships (correlation) and against multiple dependent agronomic variables to establish their influence on the device results (regression) (more detail is provided in Appendix I).

The correlation values (Table 15) show significance (*sig*) relationships (less than 0.05), signifying a 95 % confidence interval. Grass rooting has a strong relationship with the 50 mm pin results for all the plots. The native and the 80/20 had relationship to density and the 80/20, Eclipse™ and Mixto™ plot related to grass coverage. The 100 mm pin force results correlated with grass rooting in all the sandy plots and coverage in the uncarpeted constructions (80/20 and Fibresand™). The native plot had significant relationships to both water content and air voids.

Table 15 – Bivariate correlation relationships (<0.05) of the 50 mm and 100 mm pin results against the agronomic variables

Plot	50 mm	100 mm
Native	Effective Rooting, Density (Bulk and Dry)	Water Content (Gravimetric and Volumetric), Air Voids
80/20	Grass Rooting (Effective and Max) Density (Bulk and Dry), Coverage	Grass Rooting (Effective and Max), Grass Coverage
Fibresand ™	Grass Effective Rooting	Grass Rooting (Effective and Max), Grass Coverage
Eclipse™	Grass Rooting (Effective and Max), Grass Coverage	Grass Rooting (Effective and Max)
Hero™	Grass Rooting (Effective and Max)	Grass Effective Rooting
Mixto™	Grass Effective Rooting, Coverage	Grass Rooting (Effective and Max)

The regression models were used when predicting an outcome for multiple predictor variables when measured against another single variable (shear strength). The linear regression calculated the extent to which the predictor (turf properties), influenced the shear strength results. The results were inserted into SPSS and the dependent variable, the performance values (MK II and HP), were compared against the turf independent variables. The extent to which they were chosen for each turf construction was dependent on whether they had strong relationship correlation values provided in Table 15.

When input into the regression model and results were generated, the important value was for the R^2 value. This value is between 0 and 1 and details the percentile, when converted, of accountability of the independent variables to the results of the dependent variables. Therefore, a higher value determines that there is greater accountability of the turf properties, and if lower other factors are producing the result.

Another result from the regression model is the *F* and *sig* values. As stated previously when describing the correlation factors, a significant *p* value of less than 0.05 indicates a 95 % confidence value. In this case the significance value aligns with the *F* value. A high *F* value and a low significance value, i.e. 0.05, would indicate a for 0.5 % possibility that an *F* value this large would happen by chance alone.

The regression model in Table 16 and Table 17 analysed the pin forces against several variables simultaneously to find the extent to which they influenced the results of the constructions shear stability. A strong relationship is determined by a high R^2, high *F* value and a low significance value (sig) (under 0.05). If there was low significance, then these were highlighted grey in the table.

Table 16 showed, for the 50 mm pin forces, that rooting was a highly dependent variable for the different constructions, except for Hero™ and Mixto™. This would imply that rooting is an important factor for shear stability within the top 50 mm of the turf, as shown by the results for the loose soils (native, 80/20, Fibresand™) and Eclipse. These results are in line with what is suggested in literature indicating that rooting can provide strength to the turf (Section 3.4) and is more influential to strength than water content at this depth. The Hero™ possessed no significance to any combination of multiple dependent variables and the Mixto™ only showed significance when dry density was excluded. However, the inclusion of a carpeted system seems not to provide reliable results, this could either be due to the dependence of the results on only one variable (grass rooting), or the results of the Shear Tester have been affected by the interaction of the backing skewing the results. Further analysis follows in the conclusions (Section 5.6).

As shown in Table 17, the native plot with the 100 mm pin showed significant regression results when gravimetric water content was an included variable. This aligns with the properties of clay stated in Section 3.2.1. The other (sandy) plots all had significant regression models when rooting was included in the model. The exception is the Hero™ plot, which showed no significance of the dependent variables at any selection of available variables. This may again be due to the same issues as detailed for Table 16 and the data might be unrepresentative for the shear stability of the carpeted systems. However, it appears that the Hero™ systems is the only one affected by this phenomenon for the 100 mm pin.

Table 16 – Regression model measuring the 50 mm pin force against agronomic values

	Native			80/20			Fibresand™			Eclipse™			Hero™			Mixto™		
50 mm Variables	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*
Gravimetric WC, Dry Density	0.363	2.565	0.131	0.456	3.772	0.065	0.373	2.676	0.122	0.325	2.162	0.171	0.154	0.816	0.472	0.262	1.596	0.255
Effective Rooting, Gravimetric WC	0.491	4.336	0.048	0.623	7.445	0.012	0.471	4.002	0.057	0.851	25.67	0	0.369	2.63	0.126	0.721	10.32	0.006
Effective Rooting, Dry Density	0.546	5.419	0.029	0.661	8.757	0.008	0.715	11.292	0.004	0.662	8.8	0.008	0.332	2.237	0.163	0.433	3.055	0.103
Effective Rooting, Coverage	0.579	6.865	0.013	0.678	10.543	0.003	0.471	4.457	0.041	0.682	10.735	0.003	0.407	3.435	0.073	0.534	5.149	0.032
Effective Rooting, Dry Density, Coverage	0.609	4.162	0.047	0.708	6.457	0.016	0.715	6.692	0.014	0.689	5.916	0.02	0.349	1.427	0.305	0.535	2.687	0.127
Effective Rooting, Gravimetric WC, Dry Density, Coverage	0.682	3.754	0.061	0.708	4.238	0.047	0.78	6.215	0.019	0.871	11.79	0.003	0.397	1.151	0.407	0.73	4.063	0.063

Table 17 – Regression model measuring the 100 mm pin force against agronomic values

	Native			80/20			Fibresand™			Eclipse™			Hero™			Mixto™		
100 mm Variables	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*	R^2	*F*	*Sig*
Gravimetric WC, Air Voids	0.816	19.938	0	0.216	1.238	0.335	0.136	0.709	0.518	0.242	1.434	0.288	0.05	0.238	0.793	0.286	1.802	0.22
Gravimetric WC, Coverage	0.843	24.218	0	0.38	2.752	0.117	0.453	3.724	0.066	0.214	1.223	0.339	0.296	1.896	0.206	0.37	2.648	0.125
Effective Rooting, Coverage	0.008	0.042	0.959	0.704	11.877	0.002	0.584	7.022	0.012	0.505	5.098	0.03	0.35	2.695	0.116	0.663	8.853	0.007
Effective Rooting, Gravimetric WC	0.885	34.779	0	0.704	10.718	0.004	0.717	11.429	0.003	0.593	6.568	0.017	0.332	2.24	0.162	0.782	14.364	0.002
Effective Rooting, Gravimetric WC, Coverage	0.91	27.089	0	0.704	6.352	0.016	0.72	6.84	0.013	0.763	8.575	0.007	0.367	1.544	0.277	0.786	8.571	0.01

4.3.1.4 The Hand Pull Devices Assessment of Established Rootzone

The HP device was used with the 50 mm pin when the perennial ryegrass was fully matured in the second summer (> 15 months). Three tests visits were conducted with distinctly different environmental water content conditions for each, with plot averages of 7% (dry), 13% (moderate) and 25% (wet) gravimetric water content, respectively. This was useful to measure the effects of water content when grass rooting was established in the plot constructions.

The results for all the constructions (Figure 40) indicated that Eclipse™ provided the highest initial torque values in the first 10°. The native plot also had similar strength at 7 % and 13 % water content. The lowest pin force was for the 80/20 construction, followed closely by the 25 % water content Fibresand™. Most of the results for the carpeted systems were similar for all the water contents. The native, 80/20 and Fibresand™ constructions showed some differences in torque values from 7 % to 25 % water content. The backed carpets tended show an increase in torque values when the pin movement started.

The addition of strong grass growth and hybrid materials altered the curves seen in the laboratory samples (Section 4.2.9) which showed similar results to the expected stress/strain curves detailed in Section 3.2.1. Apart from the native and 80/20 plots that had followed similar curves by reaching an ultimate torque level and remaining similar, the results for the other plots tended to increase further from their initial torque value. These plots were high in sand and it may be suggested that their respective fibres and backings helped to further increase the shear strength as the pin came into contact.

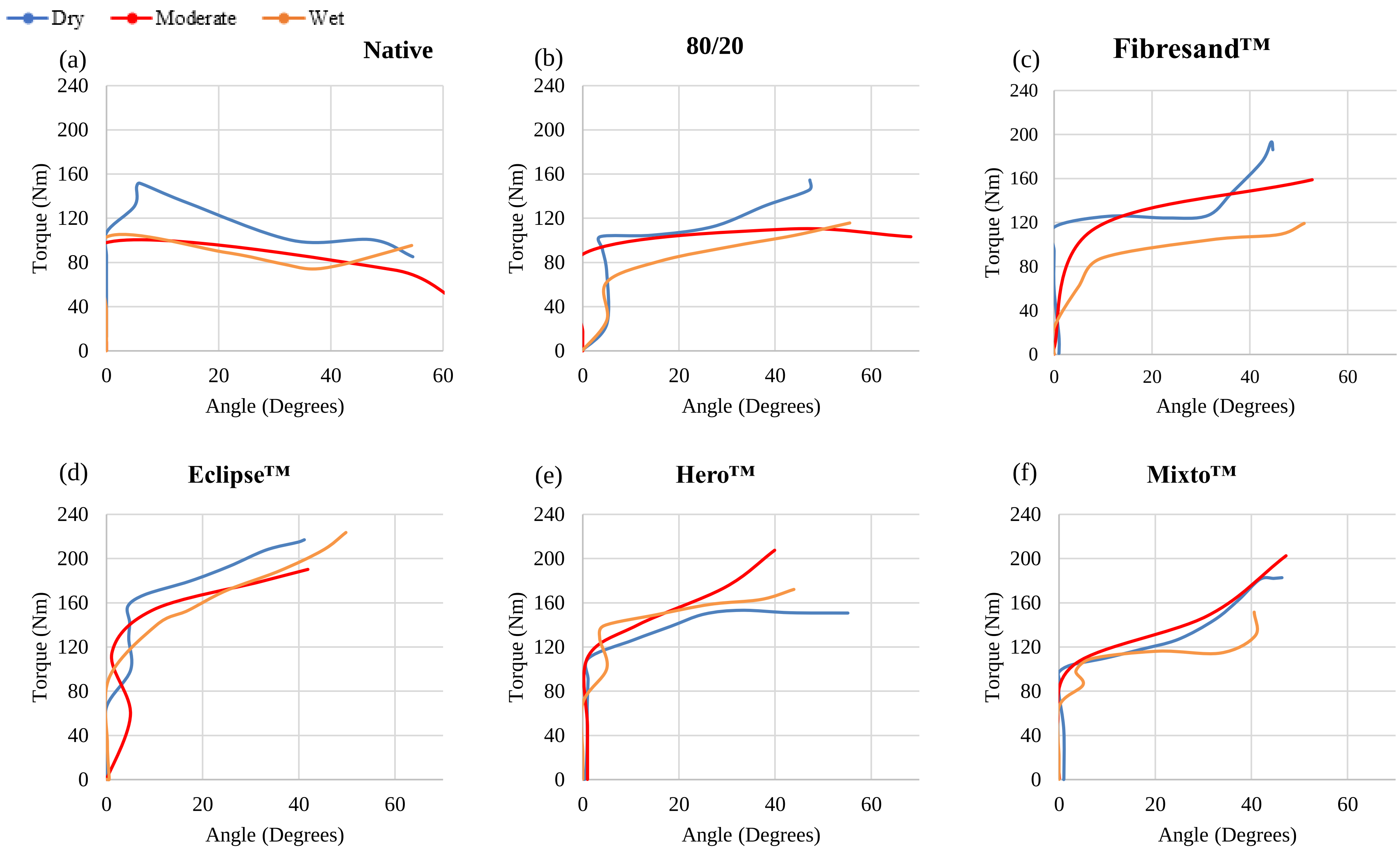


Figure 40 – Results for the Hand Pull Shear Tester undertaking tests at a dry (7 %), moderate (13 %) and wet condtion (25 %) on different turf plots constructions

4.3.2 Influence of Soil Water Content on Shear Stability

This study was undertaken in field conditions monitoring the differences in shear stability with varying water content. The MK II device measured a mid-level match sandy clay loam (clay 28 %, silt: 21 %, sand: 51 %) turf pitch which was increased to water saturation and dried out over the course of a week (further details in Appendix H).

Table 18 show the field studies' average results for the agronomic and MK II Shear Tester pin force during each test session. The gravimetric water content, bulk density, voids and air voids were calculated using a 150-mm long core. To evaluate the differences in water content to different depths the turf/rootzone retrieved was split into a top 50 mm and 50–150 mm sample. Table 18 and Table 19 detail that over the period there were no extreme changes for any of the variables as the turf dried out, but, indicate that pin force decreased when the turf was saturated. Air voids in the top 50 mm decreased in the days following saturation, followed by a decrease a few days later for the deeper 50–150 mm sample.

Table 18 – Average session data for each variable during each test visit

		Session				
	Variable	In-Situ	Saturated	Day 2	Day 3	Day 4
	50 mm Pin Force (N)	424	393	393	424	424
	100 mm Pin Force (N)	816	537	760	779	779
< 50 mm	Gravimetric Water Content (%)	21.24	28.48	25.89	26.37	25.90
	Bulk Density (g/cm^3)	1.48	1.49	1.67	1.42	1.53
	Dry Density (g/cm^3)	1.17	1.06	1.24	1.05	1.13
	Voids Ratio	0.58	0.62	0.55	0.62	0.59
	Air Voids (%)	27	19	12	25	20
50 – 150 mm	Gravimetric Water Content (%)	15.85	16.14	15.78	16.02	15.97
	Bulk Density (g/cm^3)	1.64	1.61	1.56	1.65	1.70
	Dry Density (g/cm^3)	1.38	1.35	1.31	1.39	1.43
	Voids Ratio	0.50	0.51	0.53	0.50	0.48
	Air Voids (%)	24	25	28	23	21

Table 19 – Data detailing minimum, average, max and the standard deviation of the variables

Property	Gravimetric Water Content (%)	Bulk Density (g/m^3)	Dry Density (g/m^3)	Void Ratio	Air Void (%)	50 mm Pin (N)	100 mm Pin(N)
Min	19.16	1.59	1.29	0.54	23	236	443
Max	21.30	1.79	1.46	0.61	39	613	891
Mean	16.56	1.30	1.07	0.47	14	412	734
Standard Deviation (2 DP)	1.29	0.11	0.09	0.03	5	75.32	125.05

Calculated bivariate correlation models found a strong correlation between the 100 mm pin forces (sig values 0.008 and 0.028) and the gravimetric water content for both core depths. Linear regression models provided no significant relationships between the dependent variable – water content, bulk, dry density or air voids – for either pin.

4.3.3 NOTABLE RELATIONSHIPS

In addition to the Shear Tester results it was stated in the methodology that gravimetric water content would be used throughout the study because of its more accurate readings (Section 2.4). This was investigated throughout the study and offered value to the Scoreplay™ test procedure, which used a TDR (ML3 ThetaProbe Soil Moisture Sensor, Delta-T Devices Ltd, Cambridge – – functionality stated in Section 3.7) to take water content readings. The gravimetric readings were taken from core soil samples, which measured the container mass it was placed on (m_1), the container and wet soil mass (m_2) and the container and dry soil mass (m_3), as stated in Equation 1, creating a percentage gravimetric value (British Standards Institution, 1990a).

$$Gravimetric\ Water\ Content\ (\%) = \left(\frac{m_2 - m_3}{m_3 - m_1}\right) 100\ (\%) \qquad \textbf{Equation 1}$$

Both water contents are measured differently and therefore, to be relatable, the volumetric measure was converted to gravimetric readings (see Equation 2). Where ρ_w is water density (g/cm^3), ρ_{dd} is the soil dry density (g/cm^3) and Vol_{wc} is the volumetric water content (%).

$$Gravimetric\ Water\ Content\ (\%) = (\rho_w - \rho_{dd}) * Vol_{wc}$$ **Equation 2**

The field results (Figure 41) showed greater similarity between the converted results when soil water content was lower. The native samples (higher clay percentages) showed an exponential increase in difference as the water content increased. The sandier soils had more sporadic readings as water content increased, however, there was a cluster where the results were similar at around 22 %. In the laboratory studies, where bare soils were at set target water content values, the clay tended to have a much stronger relation between the converted results (Figure 42). Fibresand™ had close relationship between water content values. The rest of the sandy materials were irregular, underpredicting the gravimetric water content.

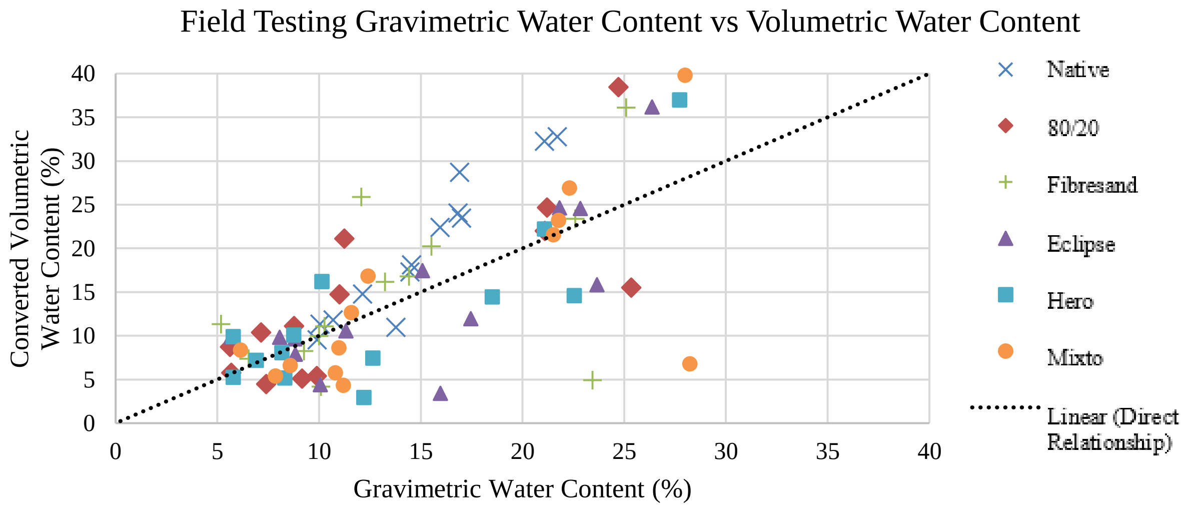


Figure 41 – Gravimetric results versus converted volumetric water content

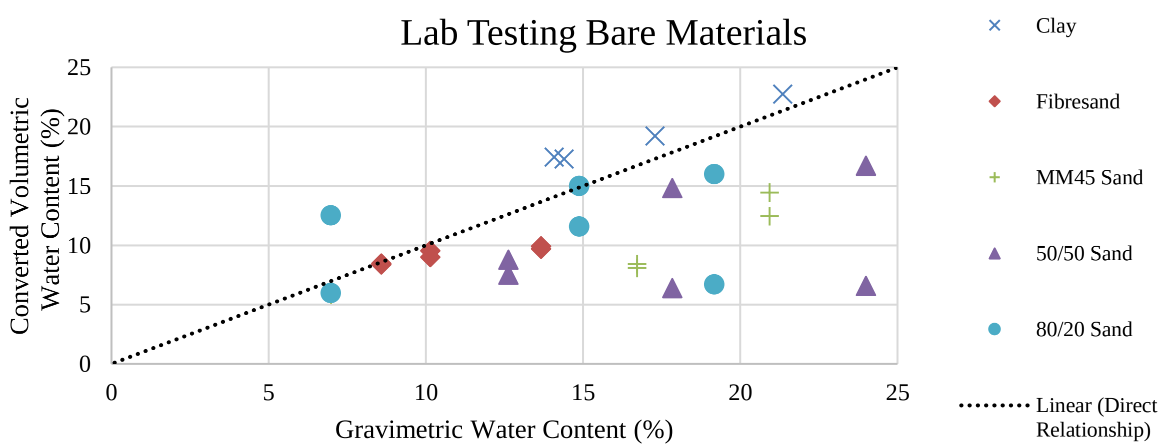


Figure 42 – Laboratory gravimetric results versus converted volumetric water content

5 CONCLUSIONS

5.1 INTRODUCTION

After validation of the device, further studies using the Shear Tester investigated the variables shown to effect shear stability (Section 4.3). Analysis of these results is undertaken in this Section. Literature was used to provide evidence of the variables shown to affect shear stability and evaluate to what extent they are an influence (meeting objective 4). Analysis further identified device functionality, evaluating the test pins, mechanics and devising a device standard testing and scoring range for the Scoreplay™ system based on the studies data set (objective 5). The device shortfalls are also discussed for player interaction relatability and shortfalls in testing across the full construction range. Moreover, the conclusions discuss the project's impact of existing theories on shear stability's, Labosport UK Ltd. and the wider industry (objective 6). The section is completed with a critical appraisal of the EngD and discussion of future work related to the project and industry.

5.2 KEY FINDINGS OF THE RESEARCH

5.2.1 VARIABLES AFFECTING SHEAR STABILITY

Three common variables were found to affect shear stability in the constructions tested: grass plant rooting, water content and density. Grass plant rooting was shown to be a strong shear stability factor for all the available construction types through the results achieved in Section 3.5, Paper 3 (Sections 4.2 and 6), the grass plant establishment study (Section 4.3.1) and the Shear Tester correlation and regression models (Section 4.3.1.3). Water content had effects, mainly on clay-based construction (shown in Section 3.3, 4.2.8, 4.3.1.3) Paper 2 (Section 4), Paper 3 (Section 5.3 and 6) and the soil water content study (Section 4.3.2). Density change mainly effected sandy construction (discussed in Section 3.3) and plate confinement test (discussed in Section 4.3.9). These variables and the outcomes of the Shear Tester studies are discussed throughout this section.

5.2.1.1 Grass Plant

Table 20 presents the increases in grasses' shear strength produced by the changes in pin forces during the study. These show that the plots had increases of between 160 % and 278 % and 70 % and 140 % for the 50 mm and 100 mm pin, respectively (individual plot construction findings follow in Section 5.2.2).

Table 20 – Percentage increase in grass plants shear strength

Percentage Increase (%)	Native	80/20	Fibresand	Eclipse	Hero	Mixto
50 mm Pin Force	213	228	278	182	160	278
100 mm Pin Force	70	140	140	140	113	140

The findings of the high sand content plot materials used for the grass plant establishment study compare closely with the results in Comino and Druetta (2009), which decribed 325 % increases in ryegrass shear strength. Comino and Druetta's method, using a bespoke shear box measuring a shear plane at 100 mm depth, appeared to produce similar results to that obained by the Shear Tester in sandy soils.

The native soil from the grass plant establishment study produced a 213 % increase. Tengbeh (1993) reported a 500 % increase in sandy clay loam. The difference can be attributed to the higher percentage of clay in sandy clay loam compared with the native plot's loamy sand. The higher clay content affects the mechanical properties, providing greater soil cohesion with increases in the percentage of clay particles.

The HP device results (Section 4.3.1.4) showed that grass plant establishment maintained the shear stability of different plot constructions independent of the water content. This indicated that, to a depth of 50 mm, the grass rooting provided composite stability to all the soil textures and plot constructions. This corroborated with a number of studies (Gibbs, Adams and Baker, 1989; De Baets *et al.*, 2008; Comino and Druetta, 2009; Serensits, McNitt and Petrunak, 2011) that detailed that an increase in the number of roots, or their diameter, can reach a greater displacement through the build-up of tensile resistance and increases in resistance to shear before peak force. This is more evident in the failure curves in the natural loose soil samples (native, 80/20), as they tended to provide a peak torque and then level out after reaching a maximum force. Reviewing the hybrid constructions, the greater strength and further increases after the initial pin movement are attributed to the plastic materials in the rootzone.

The outcomes of the investigation showed that the grass plant establishment study (Section 4.3.1) provided a suitable method for grass growth assessment from bare plots to mature rooting state. The findings provide evidence showing the large effect grass rooting has on the shear stability results, both in physical results and in statistics. The physical results showed strength increases that aligned with literature, revealing that sand-based soils (included the Fibresand™) are most dependent on rooting strength. The HP device identified that, despite large swings in water content (Section 4.3.1.4), the matured grass can strengthen the rootzone, reducing its sensitivity to shear stability, even for the clay-based plot. Statistical correlation (Section 4.3.1.3) exhibited strong relationships for both the 50 mm and 100 mm pin forces in all the construction types and regression models which, when included as a dependent variable, provided between 47 % and 87 % (50 mm) and 51 % and 91 % (100 mm) of the Shear Tester stability result, respectively. Hybrid carpet mostly, despite the reinforcement, still encountered increases in strength with grass growth but to a lesser extent than loose soils textures (native, 80/20 and Fibresand™) used, as they started with a higher initial strength (discussed further in Section 5.2.2.4).

5.2.1.2 Water Content

The soil water content study (Section 4.3.2) found that higher water concentration can be held in the upper rootzone of a sandy clay loam pitch. This is shown in Table 18, which clearly indicates higher gravimetric water content in the topsoil throughout the drying of the clay-based construction. Previous studies have shown that the addition of grass roots or additives (fibres/carpet) in the upper rootzone can hold water to a greater extent than soil texture alone (ASTM, 2010; Caple, 2011; Hejduk, Baker and Spring, 2012; Ghestem *et al.*, 2013). The 50 mm pin, when tested in the native and 80/20 plots statically correlated to the soil bulk density and the grass rooting (Section 4.3.1.3). As bulk density relates to the amount of water and solids held in the soil it is evident that water content may dictate the shear stability of this natural sports turf. The literature suggests that the plots with loose soils texture are more reactive to the changes in water content in the top soil (Paper 3, Section 4.2, James 2014; James, 2015) and re-reviewing the scrummage failures it is evident from inspection that the higher water-holding capacity of grass rooting in the upper rootzone might cause a weak shear failure plane in the soil. This is mainly in clay-based systems but was still witnessed in sandy loose soils (80/20 and Fibresand™), which could result in reduced stability.

Both the grass plant establishment and soil water content studies showed a significant (correlation) relationship between the 100 mm pin force and water content for the clay-based testing (Section 4.3.1.3). The percolation of water through clay due to gravity is slower than through sand (Beard, 1973) and provides a reason why only this plot showed a relation to water content. Grass root is largely not present or established at the 100 mm depth for the native plot and therefore the pin is interacting with the clay-based water content and density, subsequently influencing the shear stability. This finding can be supported by Table 20, which shows only a small increase in the native construction’s shear stability as grass developed. This perspective produces reasoning to why, after excessive irrigation, the surfaces have decreased stability for an allotted time.

The outcomes provided by the EngD studies showed shear stability of clay-based constructions were mostly influenced by water content. However, the loose sandy soils can also be affected as a result of the grass rooting or fibres creating increased water content in the upper rootzone. This may produce an apparent ‘weak zone’ (or failure plane) where the turfgrass is more susceptible to the conditions of higher water content, hence reducing the shear stability under player interaction. The clay-based samples for the 100 mm pin was statistically correlated to water content and, when included in regression models, accounted for a sizable 82–91 % of the pin’s force result. These findings demonstrate that this pin measures the mechanical properties of the deeper rootzone as opposed to influences of materials present in the upper rootzone. The shear stability of the rest of the sandy rootzone plots may still be assessed by the 100 mm pin but their properties make them unrelated to water. They are evaluated in Section 5.2.2.

5.2.1.3 Density

Examination of the grass plant establishment study found that both the native and the 80/20 plots exhibited correlation between the density (bulk and dry) and the 50 mm pin forces. It is widely documented that clay’s strength is influenced by increased density (Section 3.2.1 and Paper 3, Section 4.2), however, the similar size particles of the 80/20 sand makes it harder to compact unless under confinement (Section 4.2.9). As the traffic throughout the study was low (mower traffic every few days) and dry density was a suitable range, albeit low (1.1–1.6 g/cm^3) (Mckenzie, Coughlan and Cresswell, 2002). The findings can be suggested to result from increased rooting establishment. This is evident as the air voids stated in these plots (average 36 %) were above the recommended range stated by Thomas (2000) (15–30 %) giving effective grass rooting growth with little restriction and increased aerobic conditions in the rootzone. The findings were similar to Serensits, McNitt and Petrunak, (2011), who found decreased traffic caused less stress on the surface of the plots and therefore the grasses were not limited in any way, growing to their full potential into the available space.

Although the grass plant establishment study was useful in determining the influence of grass and the relationship between density and loose soils, it did not accurately depict common densities seen in sports fields. This drove the reasoning discussed in the methodology (Section 2.3) to further evaluate density and undertake *in-situ* testing. Figure 43 shows that frequently trafficked *in-situ* sandy loam samples have greater density than the native plot. The laboratory test densities provide further evaluation of how effectively the materials can compact, increasing in density.

As discussed previously, clay-based materials are more susceptible to compacting under forces applied to the surface (discussed in Section 3.2.2.1), increasing soil density. However, in terms of shear stability, using a 50 mm pin, greater values found with the low density but high grass establishment, compared with the denser clay rootzone. In the sand rootzones in the plots and laboratory, density had little effect on shear stability unless under large confinement, and shear strength at normal/low pressures only improved with established grass rooting.

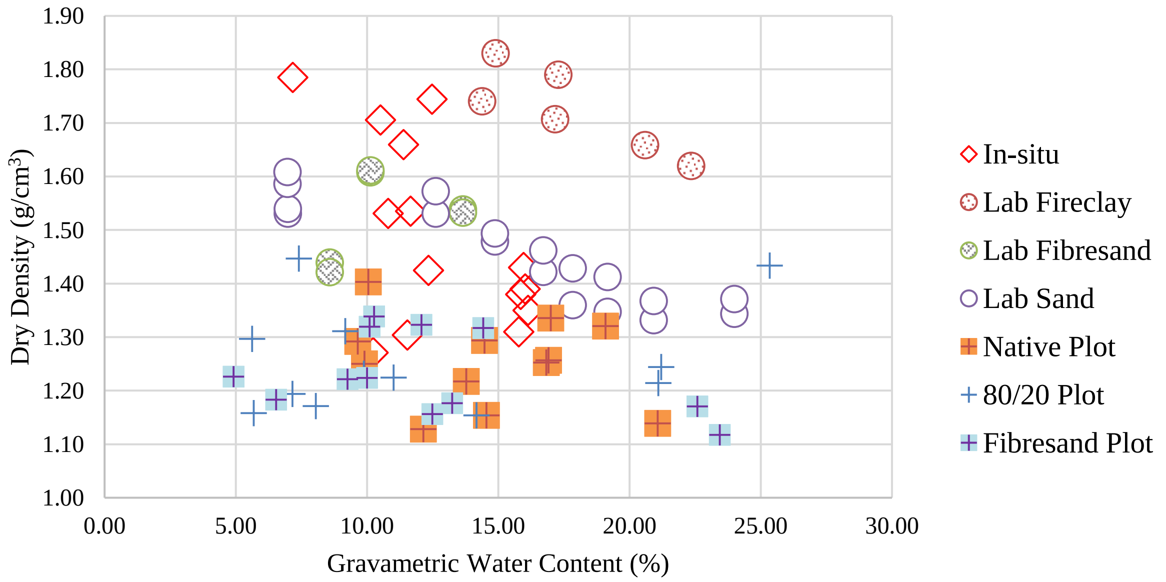


Figure 43 – Dry density of samples collected from *in-situ*, laboratory and grass establishment studies

Outcomes suggests that soil dry density is a lesser factor on shear stability compared with grass rooting and water content in soil constructions. High density in clay-based constructions, suitable to sustain grass, provides some shear stability but not as much as effective rooting growth in the rootzone. Sand-based constructions naturally do not reach the same densities as clay unless under high confinement and demonstrate that, under normal/low pressures, density has little effect on the shear stability of sands. Instead, grass rooting density was shown to have a much greater influence on the shear stability of sand-based and clay-based construction's and effective grass growth was promoted with decreased density, created using aeration techniques, increasing void ratios.

5.2.2 Factors Affecting the Shear Stability of Construction Types

The common natural and hybrid constructions are found to produce differences in shear stability as a consequence of their mechanical behaviour and influence of the variables. This section discusses the findings from the different construction throughout the study and the outcomes produced.

5.2.2.1 Native or Clay-Based Constructions

The shear stability of the clay-based constructions was shown to have high sensitivity to water content. This sensitivity was reduced by the strong establishment of grass rooting measured by the HP device (Section 4.3.1.4) and when water was maintained at an optimal level (grass plant establishment study). The native (clay-based) plot was shown to provide similar or greater stability to the hybrid reinforcement at 15 % average gravimetric water content. This is because strong cohesion between grass and clay soil texture provided a capable lattice against the pin forces. If the clay-based soil was to dry out, then shear strength would increase at the expense of player safety and grass health as it passes the permanent wilting point (see Section 3.2.1). Therefore, irrigating the turf to the appropriate level is crucial as clay-based water content is influenced largely by environmental conditions.

As indicated previously, compaction, by increasing the density, can provide some shear stability at the expense of limiting root growth (greater than 1.47–1.65 g/cm^3) (Section 3.2.1). The shear stability of clay-based pitches benefits more from healthy grasses rooting than from density, therefore, aeration techniques to loosen the surface and create a higher void ratios is essential.

The clay-based soils tested were either sandy loam, loamy sand or sandy clay loam (See Section 3.2.1). These contain varying percentages of clay in the soil texture (less than 45 % clay). As little as 10 % clay used in the native plot produced the highest shear strength of all the constructions tested. This further identifies that, if maintained to suitable water content and effective grass rooting conditions, then the native turf type possesses very effective shear stability.

5.2.2.2 Non-Reinforced Sand-Based Rootzone Material

Sand-based constructions were found to be the weakest in shear stability of all the constructions tested (Section 4.3.1.2). The use of sands such as 80/20 and MM45 have large similar-shaped particles that promote water drainage. This characteristic also means compaction is less than in clay, with the inert granular material only producing strength during confinement.

The outcomes showed that grass-based constructions strength came mainly from established grass rooting with sizable improvements in shear stability (up to 228 %). This was evident from the significant bivariate correlation (sig 0.001) and regression models that detailed a high percentage of dependency (60–70 %) for both pins when grass rooting was a dependent variable. This agrees with many studies that suggest strong grass establishment improves shear stability in granular soils (see Section 5.2.1.1). The grass plant establishment study provided the grass plant with ideal conditions (no traffic, fertiliser, irrigation) but, still did not promote better shear stability compared with some *in-situ* tests deemed to have performed poorly (see Section 5.2.3). This indicates that sand-based pitches have a set limit of shear stability that is very much below the other available constructions. Therefore, the findings, similar to the literature, provide an understanding of why clay/sand mixes and hybrid constructions are used more regularly. The cost of a sand-based construction (see Section 1.2.1) does not effectively represent value/performance in terms of shear stability when compared with a cheaper clay-based construction. Therefore, unless hybrid constructions are affordable, a clay-based construction is appropriate for suitable shear stability.

5.2.2.3 Fibresand™ Material

The grass plant establishment study Fibresand™ had a greater percentage of fine sand granules than the other sands (80/20, MM45) and PP fibres throughout the top 40 mm of rootzone. Fibresand™ had a marginally greater 50 mm and 100 mm pin shear strength (up to 28 %) than the 80/20 rootzone with low grass rooting. The shear box tests also had a greater φ' than sandy soils (Section 4.2.9). This identified that the PP fibres do improve the shear stability of the sandy soil (Paper 3, Section 4.1), and effective grass rooting further improves shear stability.

James (2011) stated that Fibresand™ binds PP together with sand to form ‘apparent cohesion’ to mimic clay (Section 3.2.3.1). Paper 3’s laboratory study (Section 4.2) found increases in shear strength with increased water content. As stated in Section 5.2.1.2, the rooting and reinforcement in the upper rootzone can hold a greater water content than the deeper rootzone. Therefore, it is possible that the PP fibres improve shear stability by holding water in the upper rootzone, creating cohesion across a larger range of water contents and densities than sand soil alone, thus producing the clay-like cohesion. This cohesion and the higher density (1.6 g/cm^3) of the Paper 3study also suggested that, when compacted, the water and PP fibres provide increasing composite strength.

Outcomes show inclusion of PP fibres in Fibresand™ produce greater shear stability than sandy soil alone. Compaction and suitable water content also increase stability and demonstrate further improvements with strong root growth, with some of the largest shear stability increases

(278 %). The apparent cohesion produced allows greater strength over a wider range than sand-based constructions, however, during investigation, there were problems regarding the distribution of fibres. This created inconsistency in shear stability readings across the material. Overall, the use of Fibresand™ offers a simple method to greater stabilise sandy rootzone pitches but it is priced similarly to the carpeted systems shown to produce greater, more consistent shear stability (Section 1.2.1). This poses questions about the true value of Fibresand™ in terms of shear stability.

5.2.2.4 Hybrid Carpeted Constructions

Investigation into the individual carpeted systems showed that carpet-backed Eclipse™ gave the highest 50 mm and 100 mm pin shear stability values throughout the grass plant establishment study. This carpet backing was not dissimilar to Mixto™ but was located 40 mm deep into the rootzone as opposed to Hero™ and Mixto™ at 35 mm and 25 mm respectively. It is theorised that the difference in pin strength results could be due to the greater rootzone depth above the carpet (40 mm), which was shown to produce the most effective and maximum root depth (Table 21).

Table 21 – The maximum and average readings for effective and maximum rootzone

		Native	80/20	Fibresand	Eclipse	Hero	Mixto
Effective Rooting	Maximum Reading (mm)	90.00	136.67	136.67	116.67	126.67	116.67
	Average (mm)	58.65	66.54	70.32	58.46	50.32	43.21
	Standard Deviation (2DP)	34.13	47.93	43.50	43.50	45.61	41.81
Maximum Rooting	Maximum Reading (mm)	140.00	186.67	183.33	170.00	170.00	163.33
	Average (mm)	81.92	121.41	113.27	99.87	82.69	80.77
	Standard Deviation (2DP)	44.26	67.36	59.75	57.72	67.14	52.50

This greater the area above the embedded carpet allowed the grass to grow more effectively, supported by the vertical fibrillated fibres, before interacting with the backing. As suggested previously, the presence of materials in the upper rootzone increases water-holding capacity (Section 5.2.1.2). Therefore, the dense carpet may hold water and fertilisers across this top 40 mm more readily than in sandy soil alone, promoting better growing conditions in the available space and more effective root density (rooting in a given area) that can penetrate further into the rootzone below the backing (Figure 44). Mixto™ had less rooting, lower root density and lower shear stability and this may be a result of its 25 mm depth and closer proximity to the surface. Further testing is needed to determine if this is the cause of the lower growth.

Figure 44 – Eclipse™ core showing the effective grass rooting

The netted Hero™ (20 x 20 mm square grid) was designed to allow grass plant to grow more effectively through the carpet while maintaining shear stability. For the grass plant establishment study, the shear stability was similar to the Mixto™ plot during initial testing to when grass established. The pin forces (50 mm and 100 mm) correlated with the rooting; however, no other variables influenced the plot (regression Table 16 and Table 17). The regression tables may have suggested no influence of variables but there could also be shortfalls in the device design (discussed in section 5.2.4.4). The findings suggest that the Hero™ netted design offered no distinct differences in shear stability qualities compared with the other carpeted constructions. There was also no large difference between water content (Table 13) or grass rooting levels (Table 21).

The grass establishment study provided ideal conditions for grass growth in the carpeted/netted constructions. However, during *in-situ* testing root growth was found to be less effective, usually failing to penetrate the carpet (Eclipse™ and Mixto™). Knowledge of soil mechanics informs theorisation that the sandy rootzone of the carpeted constructions, when subjected to high traffic may compress the sand into the carpet backing. As the sand is confined the density increases and restricts rooting growth in this area: it may also prevent water flow as freely out of the construction and into the deeper rootzone, again saturating the rooting. Hero™ netted construction may allow movement of the upper rootzone more freely but there was not enough *in-situ* data to confirm this.

Outcomes produced from the grass plant establishment study showed that the backed carpets and netted constructions were more effective in providing shear stability than the loose sandy particle plots (80/20 and Fibresand™). They initially had the highest strength when plots were bare (Table 14) and showed a smaller percentage increase in shear stability forces when grass content was established and matured (50 mm pin) (Table 20). This implies that the carpeted and netted constructions provide stability to the rootzone without the presence of grass plants but further improves as grass establishes. The significant correlation between effective grass rooting and the pin force implies that grasses influence further increases in the stability of the carpeted/netted systems. The bivariate and regression model results for rooting and pin strength in the most part were shown to increase at a comparable rate and hence show similar relationships to the other plots. Areas where they did not may be due to the device mechanism (Section 5.2.4.4). However, model results suggest that grass can improve the strength of any construction type, although sandy constructions (such as 80/20) will have a lower strength than the carpets during all stages of grass establishment.

5.2.2.5 Injected Synthetic Fibre Construction

Injected synthetic fibres systems were tested as part of the RWC study (Paper 1, Section 2) and *in-situ* tests, but were not available for the high level of evaluation during the grasses establishment study (core samples). However, to gauge the shear stability of injected fibres constructions, they were compared with other natural and hybrid *in-situ* constructions (Figure 45). This figure shows the results detailing 86 *in-situ* pitch tests. The results show that injected synthetic fibre construction, compared with the other constructions, had the highest minimum shear stability force and largest maximum shear stability force for both the 50 mm and 100 mm pins, respectively. The other plot constructions for the *in-situ* testing produced shear stability rankings similar to that described in the grass plant establishment study.

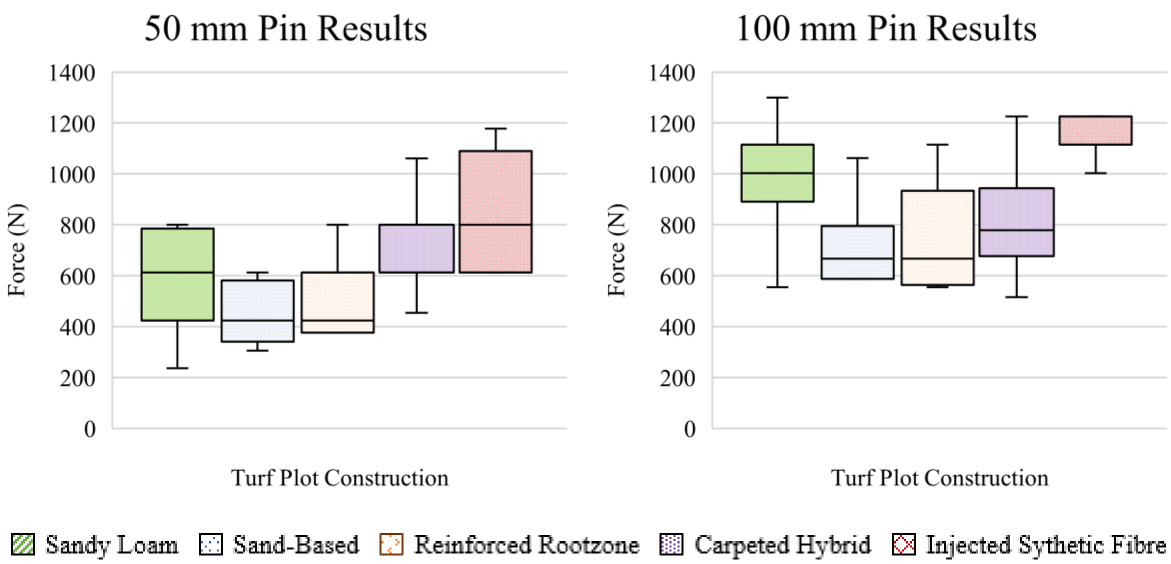


Figure 45 – Comparison in pin force values for 50 mm and 100 mm plot construction

The findings agree with the theory (Section 3.2.3.3) that the synthetic bundles provided higher resistance forces on the pin by restricting the movement of the sandy soil. Movement of the pin in the material creates confining pressure by pressing the sand into the injected bundles, hence increasing the pin force required to move the soil.

Most of the injected synthetic fibre constructions tested were in elite stadium venues, therefore the maintenance was at a superior level and could have influenced the higher pin forces witnessed. These venues were maintained at suitable water content with irrigation and density with aeration techniques. From the findings, injected synthetic fibre construction provided the highest shear stability, and high construction and maintenance costs suitably reflect the shear stability of the construction (Section 1.2.1). However, to better evaluate this construction type fully, further research equivalent to the other constructions will be required.

5.2.3 Device Relationship to Rugby Player Scrum Forces

Section 3.8.2 detailed that there were no studies available that investigated rugby scrummage player foot forces. Studies located investigated the engagement and sustained (horizontal and vertical) forces of a rugby pack and individual player when pushing instrumented scrummage machines (Table 6). The forces stated in literature were compared with the Shear Tester pin force results across the pitch constructions tested.

Figure 46 shows the calculated peak engagement and sustained horizontal forces presented for a single front-row players foot; the front row was 42 % of the total scrum force (Milburn, 1993). The calculation assumes that the force is evenly distributed between feet for each player, which might not be the case. Studies where feet were not in line on sprint blocks showed unequal force was applied to either the rear or front leg dependent on the sprinter's performance level (Fortier *et al.*, 2005). However, as no studies determined foot forces, equal force was assumed. The scrum forces were compared with the Shear Tester range of results produced for pin forces in the experimental grass plant establishment and soil water content studies.

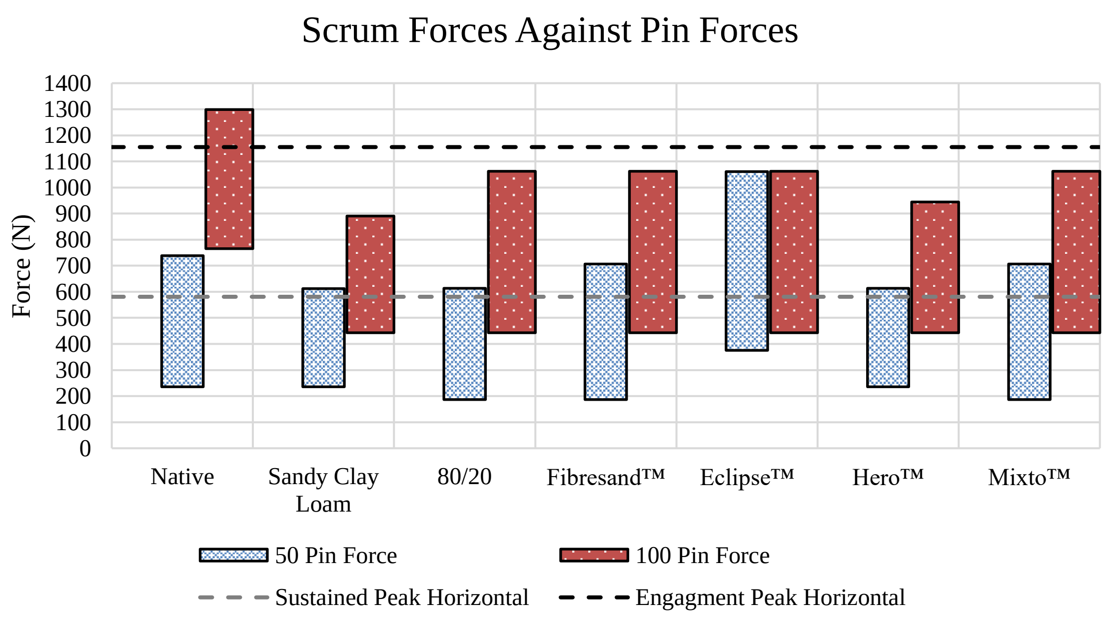


Figure 46 – Calculated single foot forces for a player in a rugby scrummage compared with the minimum and maximum shear forces produced by the 50 mm and 100 mm pins

Comparing the 50 mm pin forces and peak horizontal engagement or sustained forces, the maximum resistance for most of the samples endures the sustained peak horizontal force but fails under the peak engagement forces. Comparisons with the 100 mm pin forces show that the sustained horizontal force is greater than the minimum pin force for each plot but less than for the maximum pin force. The native plot was the only one to exceed the engagement force.

Furthermore,

Figure 47 shows the calculated rugby forces compared against the data base of *in-situ* pin results. These findings suggested similar outcomes to the results of the experimental studies, however, the 100 mm pin carpeted construction surpassed the engagement force. The only construction to surpass the engagement force for the 50 mm pin was the injected synthetic fibre constructions. For the 100 mm pin the injected synthetic fibre, carpeted hybrid and sandy loam constructions achieved beyond the engagement force.

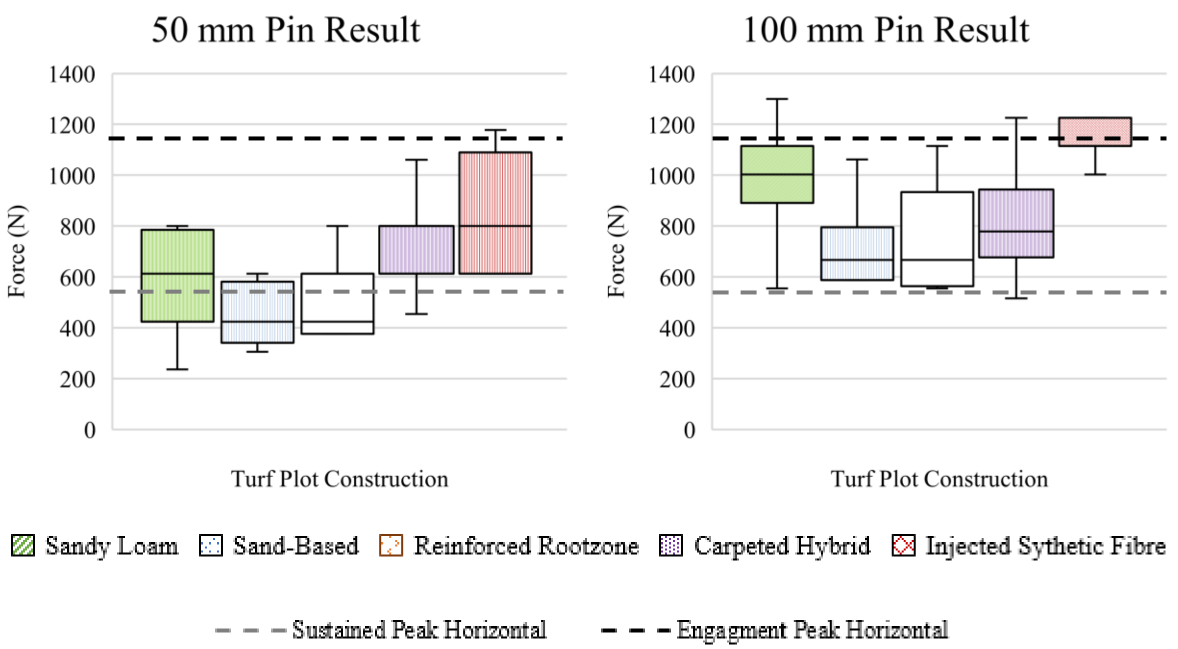


Figure 47 – Comparing the *in-situ* samples to the calculated rugby scrummage engagement and sustained forces

These comparisons do not produce a direct relationship between the scrum forces and the Shear Tester results but instead offer a simplistic comparison and indication of how much force the turf may need to withstand without incurring the effects of shear instability. The peak engagement forces were produced from a professional rugby pack prior to new engagement rules. This might imply that the engagement force listed may have reduced with new rules (World Rugby, 2017). The injected synthetic fibres produced the highest shear stability and may likely be unaffected by the high force of rugby scrummages than its counterparts. The results suggest that, to a depth of 100 mm, the rootzone may possess enough shear stability to withstand surface-boot forces without any deep failure zone occurring (as detailed in Figure 2). Other observations show that the different constructions available for both figures contain similar pin force values between the grass plant establishment and soil water content studies project's and real-world examples. This shows that study results can reflect *in-situ* cases and produce better impact from the study.

5.2.4 EVALUATION OF THE SHEAR TESTER

The Shear Tester design was evaluated to provide an indication of what the pin results provided. The Shear Tester design and mechanism was also evaluated to determine its suitability as a product to predict shear stability across the range of construction types and its relatability to player interactions on the surface.

The two pin lengths were shown to produce some similarities and differences when obtaining shear stability results during the EngD studies. A key outcome of the Shear Tester study was to better investigate the causes of turf shear stability at depth. This section, with the aid of other discussions, details what the device measures and significant properties and findings associated with the pins. The data base of results also produced from this study culminated in providing a suitable Scoreplay™ rating range and design of the standardised test method for the MK II and HP devices (objective 5).

5.2.4.1 50 mm Pin

The 50 mm pin results showed a relationship to the upper rootzone shear stability conditions, namely the presence of any materials (plant or fibres). This was present throughout the references listed in Sections 5.2.1 and 5.2.1.1, where literature complemented findings. This shear stability was apparent as the 50 mm pin produced increasing values as grass established into the constructions in the grass plant establishment study (Section 4.3.1.2). The 50 mm pin relationships showed that hybrid carpets provided improved stability to the near-surface compared with their loose soil rootzone counterparts. It also suggested that the grasses' water-holding ability may possibly create a weak zone in loose soil rootzones which may weaken the shear stability of the construction (Section 5.2.2.1). Furthermore, although bare sand soils could not be assessed with the 50 mm pin because of their weakness and the low plate confinement, there was still benefit as the device was able to evaluate the strength produced by grass roots and the inclusion of hybrid systems, rather just than sand alone. However, this low confinement also meant results are not replicable to player loading, although the 50 mm pin is still useful in providing an indication of strength supplied by root and hybrid systems in sand constructions.

5.2.4.2 100 mm Pin

When evaluating the 100 mm pin, the results suggest that the pin measures shear strength deeper into the rootzone. This was seen more readily for clay-based constructions both in the field studies (Section 5.2.1.2) and in the laboratory experimentation (Paper 3, Section 4.2) due to water content sensitivity affecting mechanical behaviour (neglecting grass influences). In sandy soils and hybrid turf the sand properties are different and the 100 mm pin identifies the strength increases of the soil with grass rooting, this is shown by increases in pin force and significant correlation, and by the similarity of 100 mm pin results for the plots when grass rooting is established (Table 14), and there is effective rooting (Table 21). This suggests that the pin is not measuring the near surface and the strength provided by the hybrid carpeted systems, but the strength produced by the grass rooting at depth.

These findings indicate that the 100 mm pin is a useful inclusion where there is possible failure or weak zone at deeper depth. These conditions can be present when assessing imported turf that has not fully knitted into the constructed layer beneath, or if there is a large difference in rootzone and subsoil texture (high sand % to high clay %). Failure at this depth would not be detected by the 50 mm pin as the imported turf has strong grass rooting and/or synthetic constructions present.

5.2.4.3 Scoreplay™ Shear Tester Parameters and Test Methodology

The database of results collected was suitable to produce a scale of pitch quality values (Table 22). This was produced with reference to the experimental tests and *in-situ* results taken simultaneously with the Scoreplay™ suite scores (RTD, CIH, AAA, ect.). The experimental tests produced from the laboratory work and the early stages of the grass plant establishment study determined the range of weaker pitch quality and if little to no grass was present. The later results of the grass plant establishment study and *in-situ* Scoreplay™ tests provided indications of the scale of the weaker range and where it fitted compared to pitches of high quality such as performance stadia. The results in-between could therefore provide a suitable range. This was achieved with individual scoring of devices and tests which were weighted into the overall plot quality and Scoreplay results. In terms of shear stability some tests such as RTD, CIH and AAA, in addition to agronomic tests such as root zone and water content (shown to influence the stability as detailed in Section 5.2.1), had an influence in providing a suitable scoring scale of categories that could be classed from good to bad. The Scoreplay™, similar to the FIFA standard, had an ideal range of suitable values and rating for each device. Utilising these ratings, and the results from tests were combined to provide evaluation of this data and produced a scoring system measuring ‘poor’ to ‘excellent’ which could be used when undertaking tests individually or in line with the Scoreplay™ test. As detailed in Section 4.2.4 and Paper 2, Section 3, a small number of Scoreplay™ tests did not provide a suitable assessment of the overall rating. For these cases, more emphasis was placed on the results from the agronomic factors, assessed with cores, and shown to directly affect shear stability as opposed to performance results.

In Table 22, the range of results accounts for a 'safe working 'range similar to that produced for the RTD provided by FIFA (FIFA, 2006, 2015). This range, produced from analysis results, ensures that the shear stability is not too high, making it less likely that players acquire an injury through twisting or jarring when their foot is planted. It is notable that in a number of cases the injected synthetic fibre construction can exceed the maximum safe results showing that although preventing shear instability during scrummaging it might inherently increase injury amongst players.

Table 22 – Scoreplay™ ratings for the two shear tester devices

Shear Tester	Poor	Average	Good	Excellent
MK II 50 mm (N)	< 327	327 –424	424–801	801–1177
MK II 100 mm (N)	< 555	555–779	779–1003	1003–1299
HP (Nm)	< 45	45–80	80–120	120–160

The extensive evaluation of the MK II and HP devices during the studies and the output of a Scoreplay™ rating scale created a means to produce a standardised test methodology to be used for Labosport operators during testing. The skills acquired in the early stages of the EngD involving developing and writing standards (Appendix A and Appendix B), producing international standards and technical reports proved useful in creating a suitable short standardised methods statement that was easily understandable to both technicians and non-technical audiences. These standardised methods for the MK II and HP devices (Appendix K and Appendix L) have been implemented into practice and are currently used for reference for operators using the equipment.

5.2.4.4 Mechanical Evaluation of the Shear Tester

The Shear Tester devices were designed to investigate the shear stability of sports turf to depth. This theory came from agronomist's review of visual inspections and assessment of sports turf after incident (Section 1.2.2 and detailed in Figure 2). Current devices available lacked the required ability to assess sports turf construction across the full range (clay, sand, hybrid) and, as higher sand content is used mainly at the elite level, it was crucial a device could assess this.

The device was designed based on specifications created from Labosport UK Ltd input and review of literature (detailed in Section 4.2.1) and aimed to replicate player interaction with the sports turf. The Shear Tester attempted to use a simple method to replicate a player's boot movement during the rugby scrummage (see Figure 20). The movement of a player's boot and the interaction with the surface have not been widely explored by available studies of the scrummage, which instead focus on the forward impact and sustained forces (Section 3.8.2). This provided some problems when considering the design for the mechanism required for the test device.

The aim was to produce a device that could assess the shear stability seen with player movement and, more so, how the fore foot stud interacts with the ground as this was visually observed from recorded cases (Section 1.2.2). In order to keep to Labosport UK Ltd specifications and to assess results with simplistic conceptual models a one pin method was chosen at exaggerated depths. This design allowed assessment to depths of up to 100 mm, although testing to this depth the mechanisms of the foot in the scrummage and the Shear Tester were fundamentally different. For the 50 mm pin, which represented a local failure produced by one boot, the minimum link is suggested between the rotational movement of a stud on a player's boot and the 50 mm pin's exaggerated length to induce shear instability failure. The 100 mm pin is used to represent the failure between players in a larger area (shown in Figure 2) and this interaction is vastly different from the pin interaction which monitors only a small area but to the required depth. Player confinement foot pressures interactions was also different from the available Shear Tester's plate. The results of the plate confinement study (Section 4.2.9) suggest the low pressure to lack ability in representing player's foot pressures and would likely have produced higher values with similar force.

Therefore, as detailed, the mechanisms are different and so relatability to player's foot interaction is minimal. The main reasoning for the mechanical design was based on specifications and literature. One of the prominent specifications was simplicity of design to limit potential malfunction of the device; this the simplicity was also dictated partly by budget constraints and lack of literature on the shear instability of turf to depth. This saw a device developed based on observed foot failure but fundamentally assessing shear stability differently. Although the device is different from player interaction, the methods have effectively assessed a form of shear stability, as produced from the results of the 50 mm and 100 mm pin data, determining shear stability across different depths. The Shear Tester in clay-based materials provides indication of strength from water content, grass rooting and density. In sand constructions, although not providing assessment of confinement, results produced from grass rooting effects can be determined. The lack of confinement is effective in assessing sand-based and hybrid constructions as pressure created by player will only increase shear stability, and the Shear Tester device determines strength without the influence of the sand confinement.

Another factor regarding the design mechanism is the pin and the applied force to an arm accelerated owing to gravity. Although the arm made the repeatability of the device more effective, the device lacked resolution in results. This lack of resolution was caused by the minimum of 5 kg weights added to the device and meant the shear strength of the constructions was provided across a range value listed in Table 8 instead of an exact value. This was later rectified with the HP device, however, although defined torque results could be achieved, the repeatability of the method was less and, as consequence, in some scenarios there could be a wider spread of data (shown in Figure 34). The test pin mechanism itself, although providing suitable readings for shear strength of most construction types, the regression models for Hero™ indicate that the device could not accurately assess this netted carpet systems. Although, grass rooting was shown to improve strength of the system, regression models gave poor results that were unexpected compared with the contradicting information from the rest of the study. The null regression results suggest that the interaction between the pin and backing in the netted system may be different each time depending on where the pin penetrated the netting, creating variation in shear stability results.

Therefore, although the device has been useful in its pioneering testing of shear stability, in order to better relate to player interactions, a new redesign is needed. This will be more complex mechanically, be able to be applied over a larger area if required, apply the confinement needed to accurately simulate player interaction and accurately assess all construction types. Future developments are further described in Section 5.7.2.

5.2.5 MEASURING DIFFERENCES BETWEEN VOLUMETRIC AND GRAVIMETRIC WATER CONTENT

The volumetric and gravimetric water content were compared (see Section 4.3.3). The results showed that when the volumetric water content was calculated to create a comparison of gravimetric water content, there was a weak relation (Figure 41 and Figure 42).

Reeves and Elgezawi, (1992) produced similar findings converting granular soils volumetric readings, which were found to be continually below the gravimetric values. This was explained by the TDR test pins penetrating the surface and disturbing the soil, creating voids and reducing device electromagnetic pulse signals. These findings explain why in the EngD studies the sandy rootzone results were lower, especially when the material particulate could displace readily (no grass plant). In addition, increased water content may be creating a greater difference in results with soil disturbance as the voids fill with water.

To better compare the water content results, the top 50 mm of the core was measured against the TDR probe, which measures the top 50 mm, as during the majority of the EngD study, water content data was taken across a 150 mm core. Therefore, to discount this difference in data collection depth, the converted volumetric value and the top 50 mm of the core were compared. Figure 48 shows the results demonstrating that there was no great significance as the difference in converted results remained similar.

Ford (2013) stated that the TDR probe was a useful quick non-destructive assessment tool for providing an approximate range of soil water content and therefore is useful in field testing and used widely by agronomists. This EngD study also suggests this, providing an approximate indication, as clay content soils had similar variances when converted, and the granular sandy soils produced irregular results. Converted values at low water content were more similar than at high water content. Thus, when suitable, to achieve a precise water content reading, the gravimetric method is more suitable albeit a longer process.

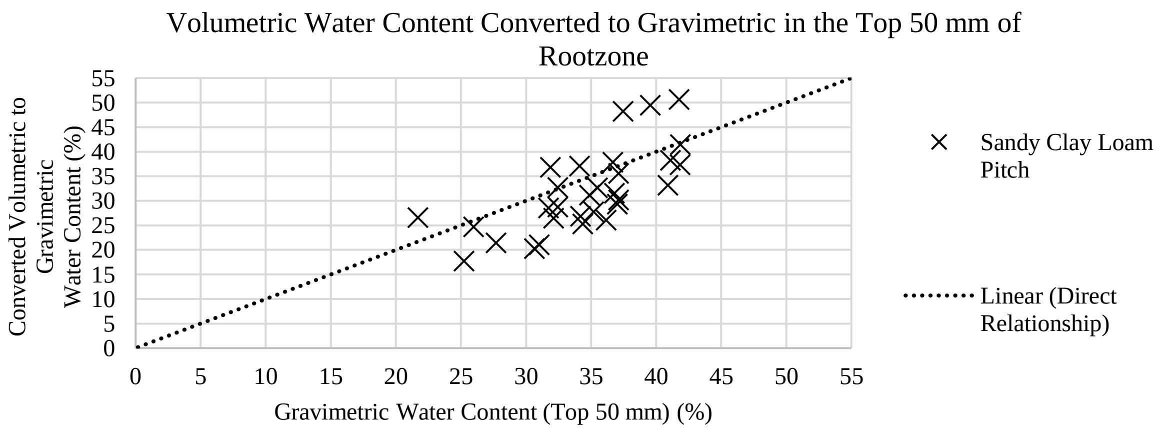


Figure 48 – Comparison of converted volumetric water content when compared with gravimetric water content in the top 50 mm of rootzone

5.3 CONTRIBUTION TO EXISTING THEORY AND PRACTICE

The EngD study produced three published papers. The papers aligned with the study aim and many of the objectives, applying the existing knowledge to provide outcomes for further research. The thesis and the papers' contribution to the subject is briefly described in this section.

Paper 1 – Contributions were made by establishing that there was a present need to evaluate the unknown property of shear stability. Evaluation of available devices confirmed that there was no effective method to test this recurring issue across the range of sports turf constructions.

Paper 2 – The Shear Tester MK I was shown to provide some understanding of the shear stability of soils under its trial study. Results showed that hybrid constructions offered more shear stability than natural turf. When the Shear Tester results were ranked and compared with overall Scoreplay™ test ranking results. The two rankings did not all always align, which showed that the current equipment for the Scoreplay™ (RTD, CIH and AAA) could, on rare occasions, not always measure the shear stability (described in Section 4.2.4), especially if it was deeper into the rootzone.

Paper 3 – Deficits in the MK I resulted in redevelopment of the device creating the MK II. Validation of the MK II assessed both the device mechanics and the effects variables have on soil rootzone properties. Variables investigation created rigour for the device, showing it measured clay materials as expected, however, the devices confinement exhibited too little surface pressure to assess the weakest sand rootzone, but instead could measure the reinforcement properties of grass and fibres in the rootzone's influence. The 'basic' conceptual model was found to overpredict the failure force and, with the matrix of constantly changing variables (water, voids, pressure), required further evaluation in the thesis.

Thesis – The further work detailed the pin mechanism and device design using the MK II and HP devices and construction variables. The 50 mm pin was shown to assess the shear stability of additives (grass/fibre/carpet) applied to the rootzone and the suspected water-dependent 'weak zone'. The 100 mm pin details stability to a deeper depth. Investigation of sand confinement closer to a player's surface interaction showed that the sand strength was increased, as would be expected. This demonstrated that plate did offer confining pressure that directly affected the pin results and did not relate to the conceptual model. Even when the model was further evaluated to output the actual results for the 7 kPa confining pressure, there were still large differences in predicted and actual force other values. This recognised the complexity of the turfgrass construction, such as water content, soil texture, soil shape and rooting effects. In order to provide a suitable model these factors would have to incorporate greater detail to predict these unsaturated rootzones.

It is documented throughout the thesis that the Shear Tester provides less confinement, than that suspected to be produced by a player's interaction (Section 4.2.2), however, it did better in assessing the degree of strength provided by grass root or hybrid construction in sandy soils (stated in Section 5.2.1.1). These strength effects were witnessed further with analysis of the HP device failure curves (Figure 40). These detailed the large effects grass plant had on maintaining rootzone strength when matured and the increased strength provided by the hybrid constructions. The hybrid constructions showed the greatest shear stability from the injected synthetic, carpeted and reinforced rootzone constructions, respectively. Clay-based pitches under suitable properties, or when dry, can also show considerable shear stability. Turf shear stability was presented against the comparable suggested scrum forces, however, as stated in Section 5.2.4.4, the Shear Tester device currently lacks relatability to player interaction and the scrumming pack movement is much more complex. This lack of relatability, although successfully providing a form of shear stability results, means that the device needs further redesign to be more replicable. These redesigns needed to provide a mechanism and confinement similar to a player and introduce a more repeatable method with a valued, precise output instead of a range. Therefore, although the Shear Tester provided an understanding of turf shear stability currently and has been developed as a working product by Labosport UK Ltd., future redesign of the device will have to try to better replicate player's interaction to fully understand the relationship of shear stability under player loading.

5.4 IMPACT ON THE SPONSOR

As detailed in the introduction (Section 1.3), prior to the EngD being established, Labosport ventured into testing natural and hybrid sports surfaces, leading to the creation of the Scoreplay™ test. After witnessing pitches with poor shear stability with no method available to test them it was determined a device would be designed to test this variable.

The EngD study provided a complete development process from the initial specifications to the current Shear Tester device. Each stage was detailed and well documented to yield understanding of design functionality and ease in fabricating more models. The validation was important to prove that device was capable of measuring the sought after shear stability in some regard, and evaluation of the test pins developed understanding of what exactly the 50 mm and 100 mm pin results showed, even if it was not completely similar to player interaction.

The Shear Tester offered the Scoreplay™ an assessment method for a variable not currently evaluated. Adding the Shear Tester and using it sizeable data set formed a quality scoring range based on a wide variety of soil quality and constructions (Table 22). This range was applied to the Scoreplay™ and the shear stability measures with both the 50 mm and the 100 mm pins were effective in providing a more comprehensive overall percentage rating for the Scoreplay™ (Section 1.3.1). This provided Labosport with a standardised test method for the company

(Appendix K and L) and a scoring product providing more reliable evaluation of sports pitch conditions.

The device's rigour and application to the Scoreplay™ test saw fabrication of several further HP devices for use by Labosport offices worldwide. The device has seen increased use and, as suggested by the popularity of the Scoreplay™ in Section 1.3.1, this could see more units fabricated. The direct impact of the study may be witnessed currently as it is being used as standard on the Scoreplay™ test to assess venues in the build-up to the Japan RWC 2019.

Furthermore, the study improved Labosport's understanding of turf construction and the influence of variables that effect turf's shear stability. It has demonstrated the requirements of good practice in irrigation and aeration techniques to promote effective plant growth and stability. Labosport offer consultation to governing bodies, institutions and high-profile customers, therefore, the information provided on the turf construction is important to produce well-defined technical advice based on fact.

Moreover, core sampling during the project was pivotal in analysis of the sports turf. Although the Scoreplay™ assesses grass health and rooting using this method, the addition of gravimetric water content, density and void ratios presents useful rootzone data in characterising turf. The core can also show differences in soil texture layers, providing an indication of which Shear Tester pin is a more suitable for testing. The results are invasive but offer greater understanding of the turf surfaces and have been recommended for use when reasons for poor pitch performance cannot be identified from Scoreplay™ tests (including the TDR probe routinely used for assessing surface water content).

5.5 IMPACT ON WIDER INDUSTRY

The natural and hybrid sports surfaces industry is growing in size and stature. Elite modern-day pitches contend with increased play frequency and consequently require increased maintenance.

When performing poorly they are scrutinised by the media's perception and by stakeholders. This places high pressures on ground staff which previously could seek an agronomist's advice. Although useful, consultation lacks perception of player performance on the surface, which may not resolve the poor performance issue. The introduction of the Shear Tester provides a useful measure of shear stability factors in pitch pre-match assessment detailing to a better extent than other performance devices the shear stability of the turf to depth. This can be used individually or as part of the Scoreplay™ suite of tests. As detailed previously, the addition of the Shear Tester to the Scoreplay™ suite of tests provides a closer relative assessment of field conditions in an easy to understand rating system. When undertaken in a suitable time-frame prior to a game, the test can deliver advice to ground staff, so that they can combat the problems and prevent the surface failing during play.

Furthermore, there are now a large number of constructions and products available on the market and although they vary, they can all fit into the wide bracket of natural (clay/sand) or the three main hybrid categories: reinforced rootzone, carpeted and injected synthetic fibre. The project combined and compared all of these construction types from study experimentation and *in-situ* testing. This extensive data set compared the shear stability of all the different constructions on a scale not previously seen in the literature. The presence of *in-situ* elite venues in the data set makes the findings of the study more applicable to field conditions, and these can be used as a guide, along with the Shear Tester score range. Furthermore, investigation of the variables influencing shear stability (water content, density, rooting) in specific constructions better informs the industry of their qualities, shortfalls and costs. The findings provide suppliers and customers with information based on independent assessment of the constructions. This is required as, surprisingly, many of the hybrid constructions do not have any readily available independent research available on their performance. The study can therefore provide advice on the best product for client's need and budget (Section 1.2.3).

5.6 CRITICAL EVALUATION OF THE RESEARCH

An important factor to include in the EngD was critical evaluation of the research to determine the limitations, understanding and effectiveness of the research undertaken and areas of improvement; this section discusses and reviews the project in these terms.

5.6.1 CRITICAL REVIEW OF THE OBJECTIVES

The aim of the project was to design and develop a device that could assess the variables that affect the shear stability of natural and hybrid turfgrass constructions. To ensure that this aim has been met, the objectives are listed below and their consequential outcomes meeting each are discussed.

Objective 1: Explore literature to define the variables that can affect shear stability of natural and hybrid turfgrass constructions under player loading.

Objective 2: Evaluate the strengths and weaknesses of the current portfolio of standard test methods and relatable equipment used to assess aspects of turf and/or soil rootzone strength.

Outcome for 1 and 2: The literature review (Section 3) provided the material on the variables of shear stability: turfgrass construction types, soil texture, water content, grass plant and density. It also, with aid of Paper 1, evaluated the current test methods for the sports surface industry and related shear stability tests in detail. This established gaps in the current assessment of shear stability to depth in sports turf and that a prototype was required to assess this property more effectively. The Rugby Union scrummage was also detailed and explored for relatable information useful for assessing the shear stability.

Objective 3: Design and fabricate a device to measure the shear stability behaviour of natural and hybrid turfgrass sports constructions.

Outcome for 3: Sections 4.2–4.2.5 describe how a device based on the findings from the literature and the input from Labosport UK Ltd. was developed. The device was an untested method based on a property that had little research, namely, shear stability at depth. Paper 2 trialled the Shear Tester indicating that it could measure shear stability, albeit not across the full force range until redesign (MK II). Further investigation (Section 5.2.4.4) detailed that redesign was needed for the device to be more similar to player interaction.

Objective 4 – Investigate the key variables that can affect the shear stability of natural and hybrid turfgrass constructions and benchmark the device measurements.

Outcome for 4: The MK II Shear Tester was validated in a laboratory study (Paper 3). Sections 4.2.6–4.2.10 provided further evaluation of the pin mechanism with the creation of the HP device. The variables were tested and evaluated, with several studies and *in-situ* testing providing an indication of the factors affecting shear stability across a range of construction types (Section 5.2).

Objective 5: Develop a standard testing and analysis methodology to evaluate in-service sports fields.

Outcome for 5: Evaluation of the large data base of results produced and understanding of the shear stability variables led to a Scoreplay™ rating for pitch shear stability, and the creation of a standardised device method for the MK II and HP devices (Section 5.2.4.3), which is used by Labosport operators (Appendix K and L).

Objective 6: Disseminate the findings into academic and industry networks.

Outcome for 6: Sections 5.3–5.5 present the outcomes and impact of the study that are useful for academia and industry. These important findings are present in the research papers, thesis and have been applied to Labosport knowledge and working practices.

5.6.2 Critical Review of the Methodology

The methodology used qualitative, quantitative and mixed research. The literature detailed the subject area, however, for the rugby scrummage, there was limited transferable research available on foot forces and movement. This produced interpretation from the high horizontal forces of the scrum instead of physical foot force results meaning results could only use calculated comparable data. This interpretation of data also shaped the device development technique as there was little direct research to go on in terms of player interaction with the surface; therefore, a number design features were incorporated to meet the specifications required for the Shear Tester device which made it practical to design from knowledge of soil mechanics and agronomy, but ineffective in fully applying to player movement and shear instability witnessed under players. However, if foot scrummage data was readily available then perhaps the device would have been designed differently, producing more suitable results in the trial study and fewer design shortfalls and alterations (as suggested in Section 5.2.4.4).

5.6.3 Critical Review of the Research Undertaken

The publication of the research papers provides a reason to propose the research undertaken was to an extent successful. It created a pioneering test examining a property not currently assessed and provided some useful data. However, although there was focus on the device, there was little published work on the findings of the shear stability of turf construction properties and variables which are discussed only in this thesis.

Evaluation of the research undertaken shows that the 50 mm pin had a greater amount of testing than the 100 mm pin. After the findings from Paper 2 were established, the small data set results steered Professional Sportsturf Design Ltd and Labosport to recommend exploring the 50 mm pin further, as this was seen to be more representative of the player/turf surface failure. The higher use was evident when using the HP device. However, further evaluation discussed in the thesis (Section 5.2.5.2) showed that the 100 mm pin measured the turf rootzone properties to a greater depth. In practice, both pins should have been evaluated to the same degree, but time constraints and company interest steered the project towards greater evaluation of the 50 mm pin.

Section 5.2.4.4 highlights that the Shear Tester in its current form is not the finished product and is required to be redesigned further to better replicate of player interaction with the surface. Although offering shear stability results, these could vary from those of player interaction. Such things as the pin mechanism, the confining plate and the addition in 5 kg weights for different force values need redevelopment to more accurately assess the full range of pitch constructions and provide similarity to player interaction.

Moreover, the majority of the academic outputs focused on the background and creation of the Shear Tester device (Papers 1–3). This was useful to create device design rigour, providing impact for both academia and industry. Yet, although the device has been well documented, the results from the large studies investigating the variables in shear stability (grass plant establishment and soil water content studies) have not. These results did not have the same exposure, with no papers produced on these topics. Originally, the grass plant establishment study (Section 4.3.1) was to be published, but, owing to time constraints the information was only produced in the thesis. These findings and the Scoreplay™ suite results will likely be converted into papers after the conclusion of the EngD.

Overall, the results achieved on the sports turf provided greater understanding of the relationships, variables and properties that affect the shear stability. Although the Shear Tester was able to gauge these factors, suggesting areas of weakness, because of the diversity of pitch constructions it cannot always categorically suggest the full cause of catastrophic shear instability seen in some *in-situ* cases. This is credited to the large variations of soil textures and constructions available and a number of factors not investigated in the study, such as the effects grass species has on the root strength. The device also could not replicate player interaction during rugby scrummage, partly due to minimal information on surface interaction under players, but also because of the basic mechanical design produced from the specifications. If more was known of the shear stability at depth this could have shaped the product differently. Therefore, further research is required to evaluate the full causes either on known problem pitches, to evaluate factors that were not assessed (grass species, turf thatch, disease, etc.) or through investigation of player foot interaction specifically to rugby scrummages (see Section 5.7.2).

5.7 RECOMMENDATIONS FOR INDUSTRY AND FURTHER RESEARCH

Some recommendations from the project were developed to further research of sports turf stability. These can be separated into the industry recommendations and further development of the Shear Tester device.

5.7.1 INDUSTRY RECOMMENDATIONS

The project has explored the shear stability of a variety of common sports turf constructions and identified their qualities after variation of the grass plant, water content and densities. The research findings can measure the instability seen in elite level sport (Section 5.5), but, during the research, there was no access available to *in-situ* pitches that had witnessed these catastrophic surface failures. Therefore, to better prevent this instability, groundkeepers could engage in a knowledge distribution network to prevent others witnessing this shear instability. This would require groundkeepers to investigate the agronomic and performance values present when/if the turf fails in an extreme manner. The data and environmental conditions could be widely distributed to be included into a database to compare properties during failure or produce a standardised maintenance method similar to the PQS framework.

Although this helpful resource would be advantageous, groundkeepers can be secretive about their full pitch maintenance practices, especially if pitches are failing. Therefore, it may be difficult to initially source the data needed in order to create a standard practice to follow.

5.7.2 FUTURE DEVICE DEVELOPMENT

The Shear Tester device underwent a long development process throughout the course of the study and at the end of the project there are still areas of possible redesign improvement.

The device was originally designed with knowledge of current sports surface performance testing devices and limited literature on natural and hybrid turf shear stability. This resulted in caution from Labosport for a largely untried method, which was reflected in the development budget. This budget restricted several features from the original design until the method could be comprehensively validated. Now these have been achieved, further improvements can be incorporated into the prototype devices, namely creation of a test more replicable of player interaction. This could offer a full new concept design provided by new specifications provided by the thesis.

With further development of the current Shear Tester, it could monitor soil failures and physical force results of the test pin as it moves through the angle to a greater extent than the HP device. Development in this direction would produce readings of force at different pin depths produced by several pressure pads. The pressure pads would be on the pins' face in contact with the soil and provide pressure readings along the pin length during rotation. This would aim to identify if the soil failure is distributed evenly across the pin or if water content held in the upper rootzone or layering of materials textures (clay/sand) creates less resistance at certain depth.

Furthermore, the methods applying weight to a lever arm (MK II device) and pulling the torque wrench (HP device) would both benefit from autonomous movement at a constant rate of force. The findings from pin forces results tended to be similar, with a sharp increase in forces as the movement began (Figure 40). This autonomous constant rate of force could be supplied by a motor or hydraulics which are connected to the pivot point to provide rotation. Review of the study findings will offer the correctly supplied force range that can be applied to the pin for testing each construction type.

Moreover, the base plate dimensions of the Shear Tester could be reduced to produce foot pressures calculated to be more similar to player interaction (see Section 4.2.9). This increase in confinement (up to 59 kPa) would be expected to produce a test result closer to that witnessed in the players foot in a rugby scrummage and therefore more accurately assess the damage this play causes. Further study investigating rugby foot forces and the relative confining foot pressure would effectively provide actual values for foot force and whether the new device base plate is suitable.

Lastly, the conceptual model could be improved by incorporating more variables into its calculation and assuming the rootzone is partially saturated (See Section 4.2.9). This would increase its complexity but allow better predictions of the contribution of turfgrass to factors shown to have large effects on shear stability: air voids, water content and grass rooting.

6 REFERENCES

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APPENDIX A INVESTIGATING THE SUITABILITY OF THE BS 8462 GOAL POST STANDARD

In 2014 the British Standard (BS) 8462 was undergoing review. BS 8462 is for small-sided football games and children's goals. The controversy regarding the standard came as, in order to remain stiff and survive the test method [1], heavy metallic materials were used for the frame. Consequently, freestanding goals that toppled due to children holding on to them had high mass and children could be crushed and/or killed. There were several documented child deaths in the UK due to goal posts collapsing [2].

Labosport UK Ltd was part of the BS committee and had been approached by goal post suppliers to make the standard safer for children. Therefore, the EngD was utilised to undertake a study to investigate freestanding posts. Posts of different mass were tested with specialist standard test equipment [1] recording the topple angles, post impact energies and the amount of force required to topple the posts. The impact energies were compared with converted head injury criterion (HIC) results to produce understanding of the topple risk to child safety.

The conclusions suggested that heavier goal posts were more suitable than lighter materials as the force required to topple them was greater and, therefore, the frequency reduced. Additional advice in order to prevent toppling suggested measuring the centre of mass (COM) of the posts and measuring the 'topple angle' – the point fractionally after equilibrium as the self-weight topples the posts forward (Figure 1). If there is more weight placed on the back of the frame, then they are less likely to topple. The recommendations were considered, which subsequently lead to the new European Standard BS (EN) 16579 being produced [3].

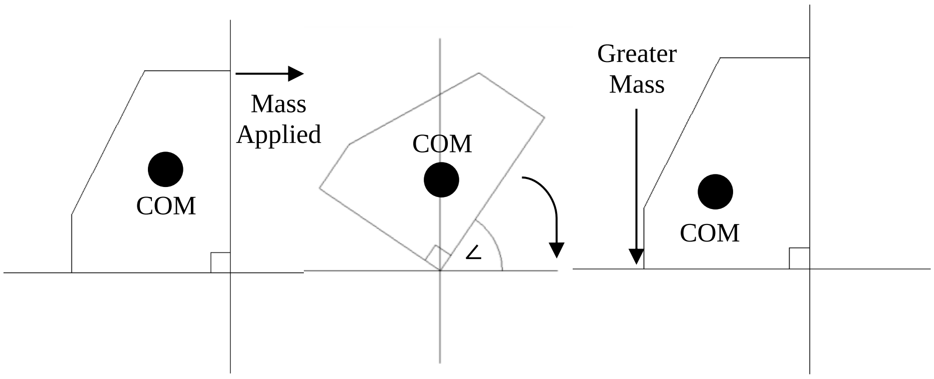

Figure 1 – **A goal post model of the centre of mass showing the equilibrium point of the posts and how the centre of mass changes when more weight is added at the back of the posts.**

This project was the first EngD work package providing development of the researcher's skill set. The findings were shared with Labosport directors and therefore presentation skills, technical and detailed report writing were all undertaken during the project. They were fitted to a tight deadline and so timekeeping was also vital. The lessons learned proved useful to the understanding of industrial outputs and was useful for future work packages.

[1] British Standards Institution (2012) 'BS 8462:2005+A2:2012: Goals for youth football, futsal, small-sided football – Specification', British Standards Institution.
[2] Pedgley, O. and Haake, S. (2002) 'Topple dangers posed by free-standing soccer goalposts', Sports Engineering.
[3] European Committee for Standardization (2016) 'EN 16579:2006: Playing field equipment - Portable and fixed goals - Functional, safety requirements and test methods', European Committee for Standardization.

APPENDIX B GPS WORLD RUGBY TEST STANDARD: REGULATION 12 SCHEDULE 3

Global Position System (GPS) devices designed specifically for sports are regularly used in rugby training and game play. They provide coaches with analysis of players movement and subsequent effort during play. However, concerns were raised by World Rugby (governing body) as there was little information on the safety of GPS devices used in rugby. A player can generate loads up to three times their body mass while running [1] (average larger professional player is 110 kg) and it was suggested under these high loads that the devices may shatter on failure and put the player's safety at risk.

Therefore, World Rugby created a consultancy group, including Labosport and Loughborough University, to develop a standard for testing GPS devices for use in rugby union. The standard was created primarily for device user safety, as the GPS devices are often located on the the player's upper back/spine between the shoulder blades.

There were several parties in the consultancy group, each with a stake in this development of the project. The initial stages of the project saw consultation on recommended possible experimental methods to the World Rugby's remit. Once confirmed by World Rugby, each party was tasked to investigate a recommended experimental method using marketed GPS devices. Loughborough investigated impact testing using a regulation rugby stud [2] dropped from height (Figure 1) and measured subsequent energies and damage created from the impact. GPS devices were tested at different temperature conditions and either as the complete product or just the GPS shell, producing a loading rate scale. Results were returned to World Rugby with recommendations for benchmarks and procedure. These recommendations, once confirmed, were fashioned into a standard format and reviewed by World Rugby for publication. The standard has now been published, becoming part of the global standard for safety using GPS devices in Rugby Union [3].

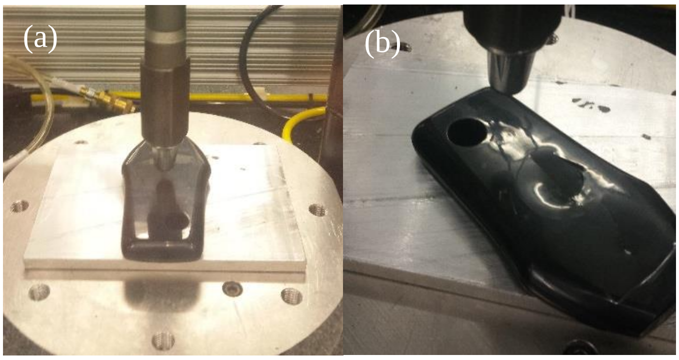

Figure 1 – Impact testing the GPS devices with a regulation rugby stud

This project provided a greater input in creating and writing up a standard method. Experience was gained, in research skills, communication and working with others in a committee to resolve and discuss finding before inclusion in the final standardised method.

[1] Lieberman, D.E. et al., 2010. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, 463(7280), pp.531–5. Available at: http://www.ncbi.nlm.nih.gov/pubmed/20111000 [Accessed July 9, 2014].

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[3] World Rugby, 2016. Schedule 3. World Rugby Performance Specifications for Players Monitoring Device. Regulation 12 Schedule 3. Available at: https://www.worldrugby.org/news/189040?lang=en [Accessed October 30, 2017].

APPENDIX C INVESTIGATING SHEAR STABILITY OF RUGBY UNION NATURAL TURF PITCHES (PAPER 1)

Full Reference

Anderson, F.D., Fleming, P., Sherratt, P. and Severn, K., 2015. Investigating shear stability of rugby union natural turf pitches. Procedia Engineering, 112, pp.273-278.

Abstract

The stability of natural Rugby Union pitches continues to be a recurring problem at all levels of the game. The effects of poor turf stability are seen when the pitch surface shears under player loading, creating divots and an uneven surface. However, perhaps surprisingly, there is no objective quantitative mechanical test method for assessing the stability of the natural turf, with regard to shear resistance. This paper details initial work undertaken to assess the effectiveness of current shear testing apparatus in predicting stability for Rugby Union. It has been suggested there are two failure areas in pitch constructions: One on the surface and one deeper in the soil. The results show variability in natural turf constructions, and that current shear test methods are less effective in sandy soils. Penetration readings were relatable to hardness, however shear stability testing requires development.

Keywords – Rugby union, Natural sports pitches, Hybrid sports pitches, Shear stability, Scrummaging

Paper type – Conference Paper

1 INTRODUCTION

Instability of natural grass turf pitches has been a problem in sports such as rugby union for some time. In rugby football, high horizontal forces generated during play can damage the turf grass and also cause shearing of the supporting soil and roots. This damage causes loss of grass cover, and undulations in the pitch surface, and potentially loss of revenue for the pitch operator. It is usually exacerbated by poor weather conditions such as heavy rain, or post freeze thaw. Recent studies on professional rugby union packs suggest peak horizontal forces of up to 13 kN can be generated in the scrum [1]. Currently the average professional player weighs as much as 110 kg, higher than for previous generations of the game, and improved physical conditioning contributes to a need for greater resistance to damage for the turf grasses. To improve turf durability a number of modern 'hybrid' pitches have been developed which include some form of soil reinforcement, or a combination of natural and artificial turf. Also increasingly sand-based subsoils are used to enhance drainage and reduce moisture susceptibility of clay based systems, but at the cost of increased nutrients needed to feed the plant growth [2].

However, there have been very few investigations into measuring the turf-soil stability. Current understanding suggests that maintaining the correct soil moisture content, drainage (infiltration) capacity and grass coverage are key factors for playability and durability [2,3]. In addition to the intrinsic strength of the soil-water mixture it has been suggested that the grass root and leaf system can increase the 'stability' of the upper soil by 300% [4]. It is well known that the balance of sand clay and silt in the topsoil and sub-sol affects the moisture sensitivity of the soil strength [5], as clay rich soils are more likely to hold water and as they get wetter deform more easily and plastically under load [6]. Best practice requires constant visual inspection, taking small cores and expert advice to maintain good turf pitch health. However, it is uncommon for routine mechanical test measurements to be taken regarding play performance or stability, unlike in artificial pitch assessments. From observation of video footage and anecdotal opinion from groundsmen, instability of the turf seems to occur by two mechanisms under the player loading. It appears that if the boot force is high enough and the upper turf weak enough then shear failure can occur between the boot studs and the turf sward (grass body, upper root in the topsoil). A second mechanism is postulated whereby the failure zone within the turf system is deeper, below the topsoil, at a weak horizon such as between specific soil layers. To date these mechanisms have not been investigated.

This paper presents part of a study investigating the engineering behaviour of natural turf, with a focus on stability. The wider study is linked to evaluation of match and training venues for the 2015 world rugby cup (RWC). The data presented explains aspects of the pitch constructions and their behaviour under different stability related test methods. The objectives included; evaluation of a variety of mechanical test methods for evaluating stability related properties of natural turf, investigation of pitch construction types, and the link between the pitch physical properties and potential for instability under load.

2 METHODOLOGY

The wider study is investigating 53 natural turf and hybrid pitches in England and Wales to both select appropriate venues for matches and practice for the 2015 RWC and to provide feedback and guidance regarding pitch quality. These indicators of quality do not currently include measures directly relating to stability. The sub-study presented here included aspects of the traditional agronomic data collection regarding pitch health and physical samples and also mechanical test methods to evaluate the behaviour of the turf under load. Turf stability and design requirements for a new test method. The agronomic data was collected by intrusive coring. The cylindrical 40 mm diameter corer was driven to a depth of 220 mm. The sample was then used to determine the grass root zone, soil textures and layers, and a probe inserted to measure moisture content (% by volume) of the layers. Grass coverage was assessed using a visual scale at each test location as a score out of 100%, and grass height measured. The equipment used in the wider study were selected to quantify aspects of the turf behaviour under load including hardness, stiffness, resistance to penetration, resistance to shear, and play performance regarding ball interaction. However, for this paper the focus is on hardness, penetration and resistance to shear by a variety of methods. These mechanical test methods were selected from the wider sport surface industry. The test methods presented here include the Clegg impact hammer (CIH) (2.25 kg) for surface hardness, the rotational traction device (RTD) for boot-surface stability, and the Going Stick (GS) which measures both penetration resistance and resistance to shear at a depth up to 100 mm. Of these the RTD is the only common test in turf assessment for sports such as rugby and football. The 2.25 kg CIH appears in some standards to assess when a surface is too hard and unsafe [7].

The CIH measures the deceleration on impact, of the 2.25 kg mass from a drop height of 0.45 m, in units of gravities (g). The RTD measures the resistance to rotation of a 110 mm diameter test disk with six 13 mm long studs equally spaced on its base. The apparatus total mass is 46 kg, it is lifted and dropped from 60 mm to ensure good stud penetration prior to rotation. The operator then rotates the apparatus with a torque wrench to determine the peak torque. The GS was developed for the assessment of horse racing track 'going'. Used by racetracks to inform maintenance and horse trainers and pundits as to the surface state. It is a simple to use portable tool, and resembles a garden spade handle with a single metal probe (100 mm long by 21 mm wide) at the base. For a standard 'going' test the probe is pushed into the ground to 100 mm and then pulled back by the operator to approximately 45° to derive the going number, a combination of the penetration and shear resistances. Previous work [8] showed some promise for the GS in monitoring turf strength of (clay based) football natural turf pitch over two seasons, and suggested correlation with the CIH and RTD. The test sites were selected to represent different pitch categories (based on soil or system proprietary type) from the pool of the wider study assessing 53 pitches (Table 1). The categories comprise: Clay Based/Native Pitch (variations of this type are very common at lower levels of competition); Sand Dressed; Sand Based; Fibresand (FS)/Fibrelastic (FE); Desso Grassmaster (DG); Mottz System. All are common systems in use, the native and sand-dressed are the most common, apart from the Mottz which is gaining in popularity

Table 1 presents the pitch types investigated in this paper. Pitches 1 (P1) and 2 (P2) are well maintained university pitches used for first-team rugby union and association football respectively. P1 is a native clay systems with sand dressing. P2 is a 2-year-old FS system. FS is a sand-based system with on average 0.3% by mass of small synthetic fibres that provide local reinforcement. Pitch 4 (P4) is a well maintained and heavily used elite rugby union training pitch, a FS system, and was reportedly due to be de-compacted. Pitches 3(P3), 5(P5) and 6(P6) are also training pitches, not so heavily used relative to the other pitches, reportedly. P3 is a well maintained 2-year-old FS system. P5 is a well maintained 6-month-old DG system. The DG system comprises of 200mm long synthetic fibres inserted into the existing turf to reinforce it, leaving approximately 20 mm above ground level. P6 has a 6-month-old Mottz system, reportedly poorly maintained. The Mottz system comprises a bio-degradable synthetic mesh with 50 mm long synthetic fibres. Within this artificial carpet 50 mm of topsoil is added and seeded to grow natural turf. At each venue the corer was used near the center of the pitch to extract a sample. The moisture probe was inserted into the core at intervals of 0, 25, 50, 75, 100, 150 and 200 mm. The GS, CIH and RTD were used in six positions across the pitch with three replicates at each position. In addition, the GS was used to take measurements at depths 25, 50, 75 and 100 mm. Grass length and coverage was also assessed at the same six positions. Coverage was a rated as good (90-100%) medium (80-89%) or poor (<80%). Weather conditions were generally dry in the period of days prior to the data collection, except at P1, P2 where some rainfall occurred the night before testing.

3 RESULTS

Table 1 presents the soil descriptions derived from the agronomy standard method (BS 3882:2007), the effective root depth (depth of the major system) and maximum root length were both derived visually from the cores. Fig.1 shows visually the soil profile with moisture contents added for comparison. The results show a large variation in water content and in general the clay soils are wetter than the sandy soils, as might be expected. P1 has a uniform clay soil texture below the top 15 mm, and a relatively high water content. P1 grass coverage was 'good', grass length was high (rugby specific) with large grass root length. P2, P3 and P4 are interesting to contrast as they are all FS systems but to slightly different depths. They all gave similar effective root zone depths, and P2 recorded the maximum root length. The FS P2-4 showed large variation in water content, P2 generally the largest (possibly due to the recent rain in the upper layer), P3 with a silty clay subsoil had lower content than P2 but a higher content than P4 comprised of a more sand. P4 also had exhibited less grass coverage. P5, with the artificial fibres to depth exhibited the lowest moisture contents in general. P6, the Mottz artificial carpet based system, caused issues such that extracting a full core was not possible. There did appear to be moisture trapped at the base of this system. The grass coverage was poor, and root depth poor, though this field was reportedly poorly maintained.
The GS results for shear and penetration resistance are shown as boxplots in Fig 2. The box plots show the full range of values measured across the 6 locations as the whiskers, the median as a solid bar, and 25% quartiles in the size of box. P4 FS system gave the highest penetration resistance at 100 mm (108 N), of any one position. A trend of increasing average resistance with depth was observed for all pitches in general.

Table 1. Pitch construction details and grass turf measurements.

Test Pitch	Pitch Construction Type	Soil Texture to 200 mm	Grass Coverage/ height / effective Root / maximum Root Length
Pitch 1	Sand Dressed	<5 mm Sandy Silt Loam 5 mm -15 mm Clay Loam, 15mm - 200 mm Compacted Clay	Good/ 60 mm /80 mm / 115 mm
Pitch 2	Fibresand	Sandy Clay Loam with fibres 10 mm, Sandy Silt Loam with fibres 100 mm Silty Clay 200 mm	Good / 20 mm / 90mm / 220 mm
Pitch 3	Fibresand	<5 mm Fibresand, Sandy Clay 5-70 mm Loam Fibresand, 70mm-200 mm silty clay	Good / 20 mm / 90 mm / 120 mm
Pitch 4	Fibresand	<150 mm Sandy Clay Loam fibresand, 150-200 mm loamy Sand	Poor / 20 mm / 90 mm / 120 mm
Pitch 5	Desso Grasmaster	<100 mm Sandy Clay, Loamy Sand 100- 200 mm synthetic fibres throughout to 240 mm	Good /20 mm / 80 mm / 90 mm
Pitch 6	Mottz System	<10 mm Loamy Sand, Sandy Clay Loam and synthetic fibres10-50 mm, Synthetic carpet 50 mm Silty Clay 50-200 mm	Poor / 20 mm / 50 mm / 55 mm

When considering averages P4 and P6 gave consistently high values. However the Mottz system has a reinforcing layer at the carpet base at 50 mm depth. P3-6 showed a large range of values across the field. The lowest penetration resistance at P1 (individual and median values) is perhaps attributed to the high water contents in the clay rich soil. The CIH results for hardness (Fig.3a) in general support pitch ranking shows higher peak deceleration (i.e. hardness) at P4, P5 and P6 and lowest results at P1.

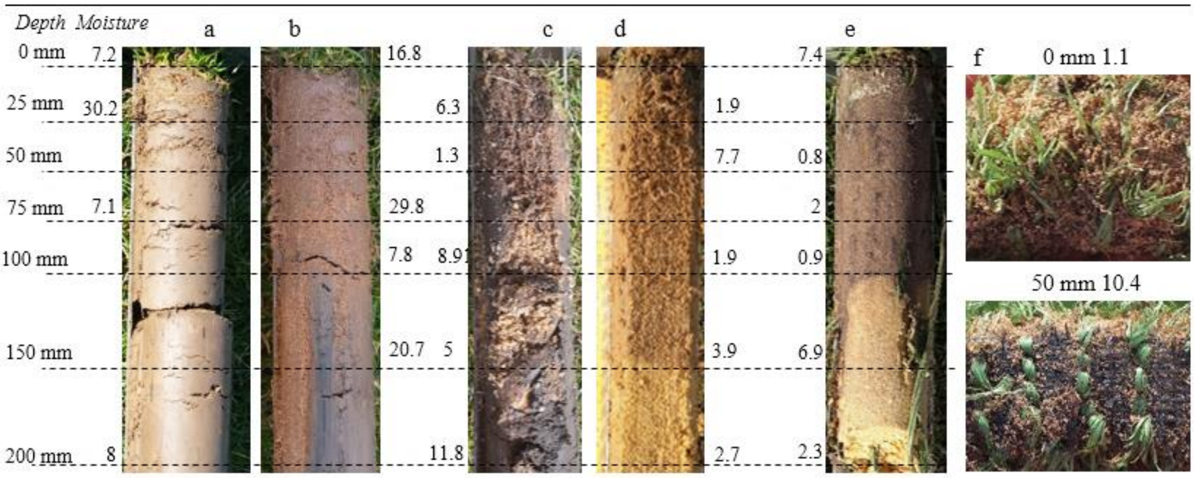
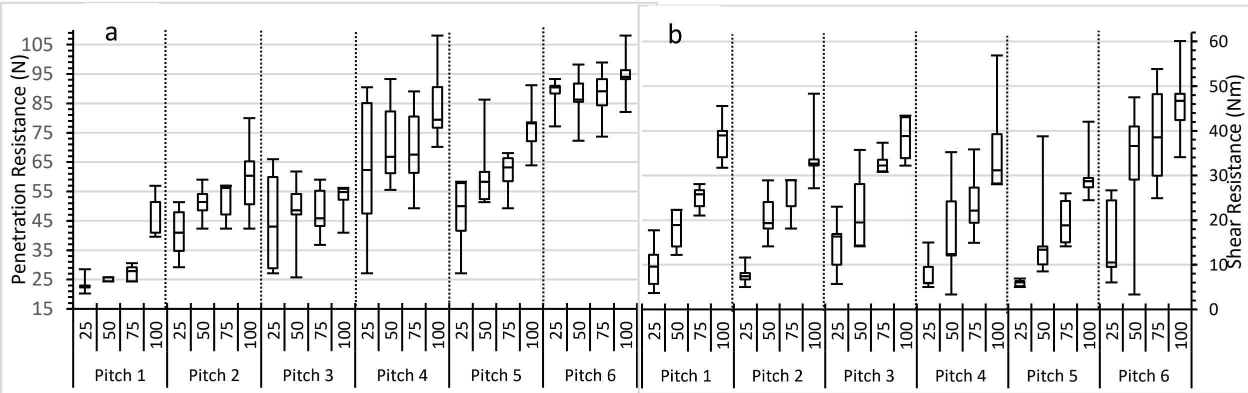


Fig. 1. Pitch sections from the extracted core samples showing soil layers visually and with moisture content (by volume) added for comparison, for pitches 1-6 (a –e) respectively. The Mottz system shown in (f) could not be cored, the diagrams show the top and base of a small sample of the carpet only.

Fig. 2 (a) Going Stick Penetration Results (b) Going Stick Shear Results



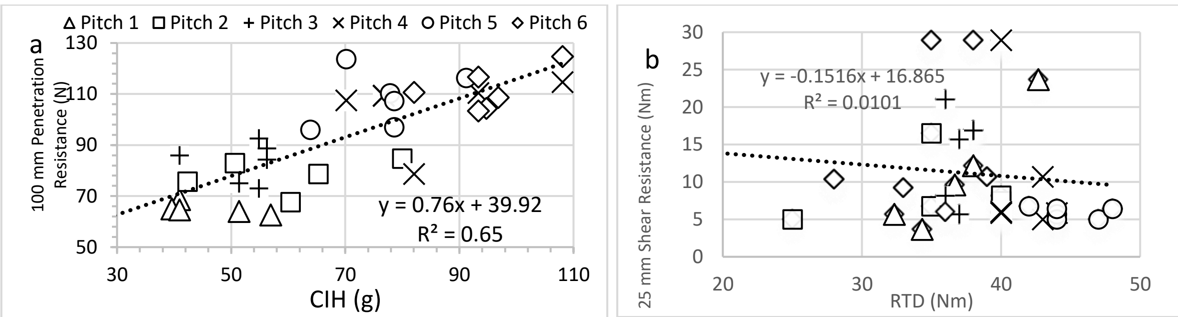


Fig. 3. (a) Average Clegg Impact Hammer vs 100 mm Penetration Resistance (b) Average Rotational Traction vs 25 mm Shear resistance

The GS shear resistance data shows a trend of increasing resistance with depth of penetration of the blade. The shear resistance at any depth is probably a function of the size of failure wedge of soil occurring along the full length of the penetrating blade. Large ranges of values are evident at each of the pitches, and in general the average values are similar between pitches for 100 mm penetration with values around 30-40 Nm. P6 is ranked the highest, probably due to the carpet base at 50 mm. The shear resistance data provide little evidence of a weak zone at any depth, and do not seem affected by the soil type, or water content. The 25 mm depth data aim to represent the upper sward, and might be expected to show a relationship to the RTD data (Fig.3b). The RTD average data show similarity across all systems at around 35 Nm except for P5 whereby 45 Nm was measured. The RTD is, however, known to have poor reproducibility, influenced by the operator [9].

To investigate potential correlations Fig.3(a) also presents the results from the average third drop of the CIH versus the GS maximum penetration resistance for 100 mm depth. The CIH has an impact diameter of 50 mm and elastic theory suggest a zone of stressing of around 100 mm. The figure shows a correlation, albeit with large scatter (R2 = 0.65). Fig 3(b) presents the RTD peak traction versus the GS shear resistance from a depth of 25 mm (representing the upper sward). The data points presented are the average of the three repeat tests at the six positions across all the pitches. There appears little correlation and very large scatter (R2= 0.01) in both data sets. This is in contrast to Caple [8] with a more positive relation between the GS and RTD. However, in his work the sports fields were predominantly clay based, in contrast to this data set which is from largely sand based and hybrid systems. It is also interesting to note however that the RTD data fall within published guidelines for rugby and football of between 25 and 50 Nm. On this basis the sward might be expected to remain stable during play. In Australia guidelines suggest 2.25 kg CIH readings should typically fall between 50-120 g, and above 120 g above 120 g being unacceptably hard [7].

4 DISCUSSION

The data gathered in this initial study has highlighted the variable range of constructions utilized in natural turf (and hybrid) systems, and a large range of water contents in the upper and lower soil layers. The pitches evaluated are at the elite level of use for matches or training. It is clear that many systems utilize sand dressing, high sand content and a bespoke FS mix – to reduce the moisture susceptibility aspects of clay rich soils and their propensity for plastic deformation and lower strength at high water contents. However, further detailed analysis of the particle size distributions is necessary to refine the soil descriptions (poor drainage characteristics outside the scope of this study). The CIH and RTD data can be combined to suggest the pitches evaluated were within the acceptable range of hardness and traction respectively. The GS was intended to evaluate if it is usefulness as a rapid pitch assessment tool, and specifically in relation to measuring resistance to shear at depth to determine if a weak layer may exist leading to a potential deeper failure under player loading. After review of the literature for soil shear related tests no other routine test was found that had this potential, notwithstanding the small hand vane and hand penetrometers used in geotechnical investigations. Although the data in this study was not included the portable hand vane was evaluated and found to provide no consistency in its measurements and was discarded – it is not recommended in sandy soils. The GS proved to be a quick and easy to use tool. However, from the data presented it is hard to conclude at this stage as to its effectiveness for evaluating general pitch stability. The penetration resistance showed some positive relation to the CIH, and a form of penetrometer may be useful in identifying layers and relative strength – albeit under vertical loading. The primary issue for rugby however is to ensure the turf and sub-soil has sufficient stability in regard horizontal shear forces.

The resistance to shearing from the tests evaluated in general showed similar average readings across all of the pitch types, with some scatter in the individual locations. It is interesting to postulate the possible reasons and mechanisms during the testing. In clayey soils (>15%) when the pores are saturated with water they behave in a specific way under load - termed undrained if loading is not very slow. The shear strength then remains constant independent of load magnitude. Strength is affected by changes in water content however. Clays also hold water with atomic electrical forces such that it is hard to squeeze water out once held within the small pore spaces. Whilst the grass root enhances the strength in principle the strength will remain stable if the water regime remains stable, hence the need for good drainage on clay based pitches. In contrast a sand rich soil (with low clay content) behaves differently and obeys classic friction laws whereby the normal force and friction coefficient control the resistance to shearing along a defined plane. Depending on the sand particle size, shape, and packing, the friction coefficient (termed angle) remains relatively constant, and is not affected by water content unless the water is confined. As a consequence, the shear strength of a sandy soil is primarily controlled by the initial state and additional load. The RTD applies a normal compressive static force of approximately 450N during rotation. An average mass rugby player could apply a static compressive force of up to 550 N (through each foot). The GS applies no such compressive force during shearing, and as such is measuring a form of unconfined strength. The GS may show relative differences in the shear resistance of turf samples but cannot replicate the static compressive loading. In a clay rich soil however, the GS may prove to be a useful indicator (from frequent monitoring) of the effects of changes in water content by assessing changes in shear resistance as has been demonstrated [8]. It seems appropriate that a shear stability test for turf may need to apply appropriate compressive loading during shear. Whether the RTD device applies an appropriate static load and whether the large strains it applies before reaching a maximum are applicable to the behaviour of the turf under a rugby player loading is more debatable [9].

5 CONCLUSION

The study investigated the shear stability of natural pitch constructions using a number of methods from agronomy, performance testing and trailing relatable equipment. The core results suggest that the elite level pitches are varied in their construction and hybrid systems are prevalent to improved durability. In general mechanical testing suggested the sandier soils gave higher hardness. GS shear resistance showed no differences between the soil types, however results suggested correlation between the CIH and GS.

The authors kindly acknowledge Turftrax Ltd. for the loan of the Going Stick

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APPENDIX D DESIGN AND DEVELOPMENT OF A NOVEL NATURAL TURF SHEAR STABILITY TESTER. PROCEDIA ENGINEERING (PAPER 2)

Full Reference

Anderson, F.D., Fleming, P., Sherratt, P. and Severn, K., 2016. Design and development of a novel natural turf shear stability tester. Procedia engineering, 147, pp.842-847.

Abstract

The stability of natural Rugby Union pitches continues to be a recurring problem at all levels of the game. The effects of poor stability are seen when the pitch surface shears under player loading, creating unsightly divots and an uneven and potentially injurious surface. This observed instability is a real concern for many stakeholders, from the groundsmen to the revenue-generating television companies and is arguably increasing caused by greater popularity of sports, more intensive use of natural turf pitches and advances in player physical conditioning. However, perhaps surprisingly, no objective quantitative mechanical test method currently exists for assessing the shear stability of the natural turf prior to games being played. This paper presents the findings from a (ongoing) research study into the design and development of a prototype turf stability apparatus ('Turf Tester'). The key aim was to measure the shearing stability of natural and hybrid turf in order to assess a recurring failure problem. In order to be relatable to sporting performance, this failure imitates conditions to simulate player(s) interaction. The prototype and test method was developed with properties suggested from published papers discussing rugby and agronomists' experience. It was theorized that there was a potential zone susceptible to failure within the top 100 mm of the sports turf. The position of this zone was variable and depended on pitch construction. The prototype was built to explore this variable failure zone using a 50 mm and 100 mm pin that sheared through the soil when a known load was applied to it. Both the Clegg Impact Hammer (CIH) and the rotational traction (RTD) were suggested to be relatable to penetration and shear stability; however, their relatability to the failure zone was an unknown. This paper details the background behind the study, the prototype design and principle, the observed failure mechanisms of sports turf, and presents the results of the prototype apparatus trailed on a range of turf constructions at venues used for the 2015 Rugby World Cup. Data was collected at each venue using Labosport's Scoreplay system detailing full agronomic classifications and a suite of industry standard player performance tests. The combined data from 13 of the venues provided a powerful data set to evaluate and refine the prototype apparatus, providing validity of its conceptual design. The findings show that the shear tester assessed the upper level of ability of pitches with a 50 mm depth pin and the lower ability with the 100 mm pin. There was some evidence of a relationship to the CIH and RTD, albeit weak, and it was concluded the shear tester was assessing a characteristic of the sport turf not currently measured by standard industry tests currently utilized. The shear tester differentiated between the high stability of the hybrid pitch constructions and the weaker natural pitches. The shear tester rankings for pitch quality also approximated well the ranking from the Scoreplay pitch quality system. Incorporation of the shear tester into routine pitch evaluations could benefit a scoring system approach.

Keywords – Rugby Union, Natural sports pitches, Hybrid sports pitches, Shear stability

Paper type – Conference

1 INTRODUCTION

Rugby Union is a physical game that has continuously evolved, creating faster play, increasingly athletic players, and with many technologies improving the game. However, despite all the advancements in player welfare and their personal equipment, it is still common to observe problems with the playing surface used. In particular, low shear stability of natural turf is a recurring problem, and is observed as the surface cutting up under the players' boots, often in scrums. This is a concern as player safety is potentially compromised; furthermore, it creates challenges for groundsmen to rapidly repair the pitch, and is an annoyance for stakeholders as popularity grows for the game and aesthetics are important. Surprisingly, there is no standardized test method for assessing the shear stability of natural turf or hybrid turf systems. Natural turf comprises predominantly clayey soil, some have top-dressing of sand, while hybrid systems have synthetic fibres present to reinforce soil and increase stability. Common hybrid systems are the Desso grassmaster, which injects hundreds of synthetic fibres vertically into the ground to a depth of 200 mm, and stand above the surface to a height of 20 mm, and Fibresand, which has millions of randomly orientated short thin plastic fibres mixed with sand to form a rootzone. A more recent 'hybrid' system is termed 'Mottz', which comprises a 50 mm long-pile (3G) synthetic woven into a permeable mesh backing. Soil is added and natural grass grown that interweaves with the synthetic fibres and through the mesh backing. These systems have been established to improve the durability of the surface and they seem to be successful with many top-flight UK sports venues to accommodate the large number of fixtures and short pitch recovery times.

Rugby players are developing greater body mass, and trends also show them being taller and younger as the game has progressed [1]. An estimate for an upper limit of rugby player mass was reported as approximately 110 kg [1]. When the turf is subjected to the high-sustained forces players can apply through their studded footwear, sudden failure of the turf can be observed (Fig. 1.b). Sustained forces are present in the scrum where players combine to create very high horizontal pushing forces of up to 8.3 kN over periods of several seconds [2,3].

The instability of the turf under high shear forces could be induced by a number of factors; these factors may include high moisture, poor grass coverage/health and shallow root establishment. Moisture content in clay soils is more critical to behavior and has a larger effective range compared with sandy soils. Clays retain more moisture and are more susceptible to plastic deformation under load as they become saturated; sand drains water more quickly and relies on inter-particle friction for shear strength. The grass roots help hold the soil together and reinforce it, and it has been shown that roots can improve shear resistance by up to 300% [4]. Therefore, having a full coverage of grass throughout the field with a deep healthy root will aid against shearing of the turf.

It was hypothesized from detailed discussions with specialist sports pitch agronomists and groundsmen that when shear instability occurs the failure zone(s) is typically within the top 100 mm (Fig. 1.a), often where there is a distinct change in the soil properties (e.g. texture, moisture). The depth of the failure zone was considered to be variable in their experience, as a consequence of variations in the construction profile and also the state of the turf–soil system. A related previous study had suggested a rationale for two distinct failure zones [5]: a shallower one in the sward and a deeper one in the sub-soil.

At present, there are no specific performance test methods aimed at detecting the shear stability of a sports pitch. Several performance test devices have previously been investigated and shown to provide some link to pitch shear stability but none has been routinely utilized in the industry. One such test method, the Going Stick, was successfully developed specifically to assess horse racing track quality or 'going'. A 100 mm long and 21 mm wide plate is inserted into the soil manually and the penetration and resistance to rotation (shear) is measured. It was trialled as a possible tool for sports pitches and assessed against the Clegg impact hammer (CIH) and Rotational Traction device (RTD) [6] on clayey soil based pitch constructions. The CIH measures the impact hardness (via peak deceleration) of the surface using a 2.25 kg mass dropped at a set height (0.45 m). The RTD is a weighted (40 kg) studded disk that is placed on the ground and rotated to record the peak resistance (torque) (Fig. 2.b). The Going Stick penetration resistance showed some correlation with the CIH, and for shear with the RTD torque also. However, a further study [5] evaluated the Going Stick across a wider range of pitch construction types, including natural soil based (Fig. 1.c), Desso Grassmaster (Fig. 1.c), Mottz and Fibresand. The study concluded that the Going Stick was sensitive to variations in shear stability of natural soil constructions, but it showed poor sensitivity or repeatability and less applicability on pitch constructions that utilize a large proportion of sand or reinforcement (hybrid) – and these latter systems are popular for their durability. Clay soils under low normal stress can generate shear strength from suction in the pore water/air interface, and show similar strength whether confined further or not. However, sand as a frictional material reacts differently: when unconfined under low normal stress it can be sheared relatively easily but, when confined, particle friction and resistance to dilation can mobilise much larger resistance to shear. The Going Stick provides no confinement and consequently measured unexpectedly low shear resistance in high sand content soils. The shear resistance in the sandier soils under a Rugby player is considered to increase though the vertical forces/stresses applied, thus suggesting a need to manufacture a mechanical device that could simulate the rugby related performance more closely.

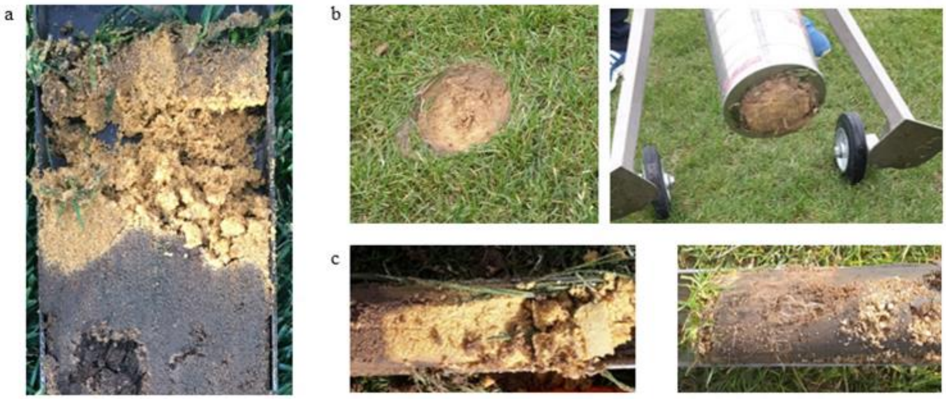

Figure 1. (a) Soil Profile with Distinct Soil Variation (b) Rotational Traction device (RTD) irregular catastrophic failure of sand top-dressed natural pitch (c) Soil profiles: (left) Desso Grassmaster system with synthetic fibres through structure; (right) Sand top dressed natural soil pitch with agglomerated sand in it’s structure

2 METHODOLOGY

2.1. DESIGN OF THE SHEAR TESTER PROTOTYPE AND DATA COLLECTION

The prototype shear tester (Fig. 2.a) was developed to include the important factors of how the turf might fail under rugby related player loading. The design was aimed at a simple mechanical test to measure stability up to a depth of 100 mm, be portable, and utilize the operator’s mass to create the required confinement in the failure zone (110 kg ideally over a suitable area). It also needed to be easy to use and interpret, and be readily modifiable if required after initial trials.

The prototype works by a simple lever arm principle to rotate a pin through the soil to assess the shear resistance. The initial angle of the arm is set at 52° from the horizontal. Two pin lengths are used, 50 mm and 100 mm, both cylindrical 20 mm in diameter and with a curved 5 mm radius at the base, resembling a (long) rugby stud. The pins are hammered vertically into the ground before the lever arm is released, applying a static force. The two pins lengths were selected to allow investigation of shear stability at depths up to 100 mm.

The lever arm (Fig. 2) transmits a force to the pin, through mechanical advantage, to attempt to fail the turf. The arm has a mass of 11 kg, and further mass can be added in 5 kg increments at a distance of 0.5 m from the pivot point. The arm is initially supported in the start position (52° to horizontal) by a simple (yellow) latch, which is manually pulled to release the arm. As the force is placed on the pin the soil either offers enough resistance to keep the pin stationary or it starts to yield and the pin moves. If there is no yield in the soil when the arm is released then the test is reset at another point and further mass is applied until failure is observed or mass limit is reached. This pin rotation mechanism aims to represent the rotational movement of a player's forefoot stud during a scrummage. As the player pushes forward, they rotate their foot lifting their heel and applying more force to the front foot. The bend of a player's foot is never greater than 27° [7]. Studies on maximum horizontal pushing force (8.3 kN)[2] suggested a resultant force of 1.04 kN per player applied into the surface.

When falling from 52°, a soil failure was indicated by an angle greater than 27°. This was used because of the physical range of a player and the visual plastic deformity observed in soils trials over this value. Prior to this, the ground was visually unchanged. During failure, a potentiometer measured the angle and the time or rotation (see Fig. 2.b), it was translated into a gradient representing rotation rate for further analysis. The angle and time of failure show a variety of modes of failure during testing. These were defined by the failure speed. Speed was categorized as either 'rapid failure', which quickly reached failure, or 'slow failure', which had some hesitation in reaching failure. Hesitation was likely caused by soil strength, root growth or synthetic structures in hybrids pitches.

The base plate area in contact with the surface was 0.177 m2. The contact stress is 6 kPa when the operator stands on the base plate, a mass of 110 kg/1079 N is attained. This represents the common weight of the heavier English rugby premier league player [1]. This area of stress may be less than a rugby player would create, but it allows weight to be applied to the device through the technician's feet, without encroaching on the mechanism.

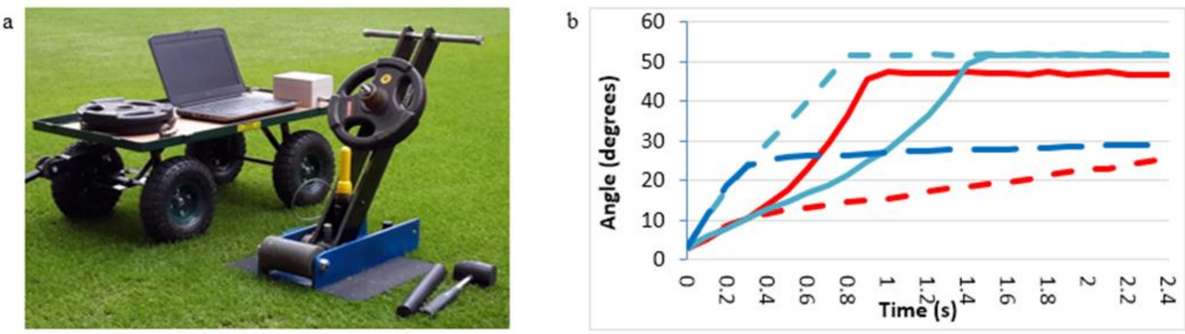

Figure 2. (a) Shear Tester (b) Time vs Angle Shear Tester Graph Example

2.2. OVERVIEW OF SCOREPLAY SYSTEM

Scoreplay is a system created by Labosport International Ltd. It determines an overall score to represent a measure of the 'quality' of natural and hybrid pitches. A combination of agronomy tests (measuring turf health and physical properties) and sports play performance tests (measuring grip and ball bounce, for example) are used to create a percentage rating for pitch quality. Pitches that scored above 85% were rated as excellent quality, between 70 and 75% were rated as good, between 60 and 70% rated as requiring attention and a score below 60% rated as requiring urgent attention. The system was developed to provide feedback to the groundsmen of the match and training venues for the Rugby World Cup (RWC) in England, and involved site visits for a period of 1 year before the competition on hybrid and natural systems. The Scoreplay percentages were compared with the results from the shear tester, with the intention that the outcome might help inform the development of a pitch rating score from the shear tester. In addition, the shear tester results were compared in more detail with those collected from the CIH (hardness measure) and the RTD (peak shear related resistance to studded disc).

3 RESULTS

3.1. TABLE OF RESULTS

Table 1 presents a summary of the results for the shear tester. Each of the 13 pitches tested (10 natural and 3 hybrid) had three positions tested with both the pins. The Table's failure mass represents the positions of failure during testing. The percentage of failures demonstrates the proportion of pitches that succumbed to failure. Gradients indicate fast (lowest) and slow (highest) failures. The natural soil based and hybrid systems percentiles were separated to show any differences in their stability.

Table 1. Pitch Shear Failures

Pitch Type	Pin Length	Failure Mass (kg)	% Of Failures	Lowest Gradient	Highest Gradient
Natural Soil Based Systems	50 mm	11	90%	0.342	1.301
		16	10%	0.24	1.348
	100 mm	26	3.5%	1.550	
		36	3.5%	2.380	
		41	10%	0.787	1.882
		56	3.5%	1.308	
		>56	80%	n/a	n/a
Hybrid Systems	50 mm	11	11%	0.788	
		16	45%	0.17	1.334
		21	33 %	0.692	0.84
		26	11%	0.693	
	100 mm	41	11%	1.247	
		51	11%	0.640	
		56	22 %	0.336	0.493
		>56	56%	n/a	n/a

3.2. PITCH RANKINGS

The results obtained from each pitch construction type, soil-based natural (N) and hybrid (H), were compiled into a ranking system (Table 2). The Scoreplay system is presented in percentile scores with the 50 mm and 100 mm pins scores placed in rank. Pitches with the same ranking scored at the same level.

Table 2. Pitch Rankings – comparing the Scoreplay rating with the Shear Tester Prototype

Pitch Type	Scoreplay (%)	50 mm Pin	100 mm Pin
N	97	9	12
H	96	2	11
N	96	8	1
N	94	3	1
N	93	5	1
N	92	6	1
N	92	7	10
N	92	10	1
N	91	11	1

H	90	4	1
H	90	1	1
N	82	12	13
N	68	13	14

3.3. SHEAR TESTER RELATIONSHIP TO CURRENT PERFORMANCE TESTS

The shear tester results were further compared against the results from the CIH and RTD (as shown in Fig. 3). The Figures show that there appears to be little relationship between the CIH (peak deceleration in g) and the RTD peak torque, for either the 50 mm or the 100 mm pins for the natural or hybrid systems. The best relationship of those selected was the 100 mm pin compared against the CIH.

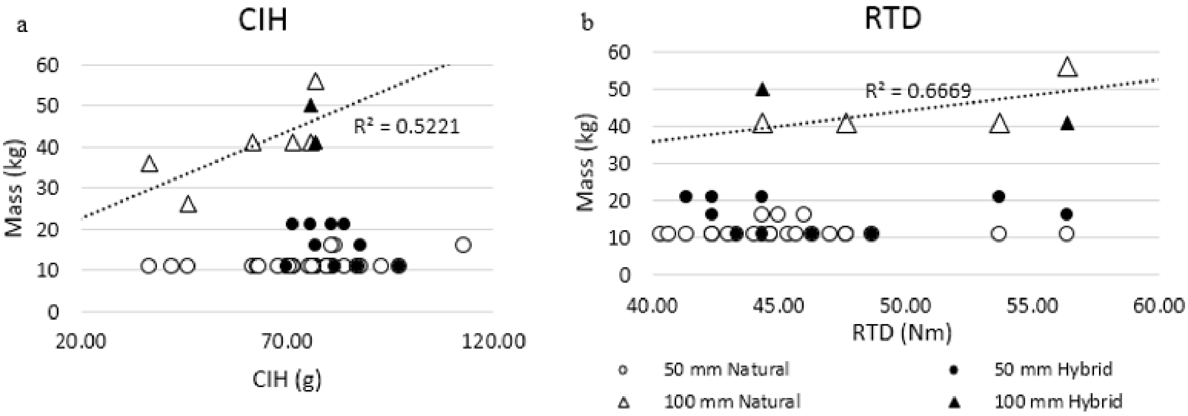

Figure 3. (a) Clegg Impact Hammer (CIH) peak g vs Shear Tester (b) Rotational Traction (RTD) torque vs Shear Tester

4 DISCUSSION

4.1. PROTOTYPE SUCCESS IN DETERMINING TURF STABILITY

The shear tester prototype presented here is an initial attempt at the analysis of a sport turf's shear failure behaviour. The shear resistance was assessed by applying a rotational force to a pin to pushing it through the turf system at a set depth of 50 mm or 100 mm. The key objective was to create a method that could accurately measure the differences in shear stability of different varieties (natural, hybrid) of sports turf. In addition, the prototype's repeatability, practicality, portability and user friendliness were all-important traits also evaluated to ensure the final product would be successful.

The results from each of the pitches given in Table 1 identified a number of outcomes for the assessment of the pitch's construction with the shear tester. It identified that the hybrid systems could survive larger applied mass with both the 50 mm and 100 mm pin. This was as expected because of the inclusion of the synthetic structures designed to reinforce the soil, stabilizing it more than grass alone. These hybrid pitches have been introduced into many top level stadia as they support the soil and poorly established grass which tends to grow in this scenario. Although some hybrid systems failed with the 50 mm pin at the lowest arm mass available, this minority was at a 'slow' failure, which was minimal compared with the 90% failure of natural soil based pitches that failed at a 'rapid' rate at the same level. The hybrid pitch that failed at low mass experienced water-saturated conditions during testing. The 100 mm pin showed a large majority of trials that did not fail with the available mass. However, the natural soil pitches had a higher number of failures at lower masses than the hybrid systems. This indicates that the Desso Grassmaster and the Mottz system are effective in supporting the soil strength and are less sensitive to the variation in the weather conditions present than the natural clay systems.

Table 1 shows the low and highest gradients, indicating that the failure rates of the turf did not demonstrate any clear variations as mass increased. Natural clay pitches are all near-unique in their construction and are inconsistent because of fluctuating moisture content. The database of pitches would have benefited from a more sensitive range of masses applied to the soil when using the 50 mm pin and greater mass applied when using the 100 mm pin. This would better indicate variation in each pitch and their failure gradients. It would also aid in better determining the factors (i.e. moisture, grass depth, soil texture) that may play a part in the soils shear strength.

The rankings produced in Table 2 suggested only a loose relationship between the two pins and the Scoreplay system. This relationship was most noticeable with the lower Table results. When small margins existed between the Scoreplay percentages (the natural soil pitches of excellent quality), the results were ambiguous with no clear comparison to the shear tester. As most of the pitches were of a similar (excellent) quality this was a hindrance in getting a fully reflective study for the whole range of pitch stability. The fact that only three different hybrid systems were measured compared with ten natural soil-based systems implies that more hybrid fields should be tested. Another key issue is that the shear tester found that the hybrid stadium pitches possessed some of the best stability. This demonstrated that the failure zone can be a problem that is not currently assessed in a quality assessment of the turf. The addition of the shear tester to this study would likely aid in giving the Scoreplay a more reflective answer of the overall pitch quality.

It was noted that after testing was underway that the forces on the pins were different from the predicted range. As stated previously, this was a hindrance in getting sensitive results. However, based on the data achieved from the failure planes, the relationship between the 50 mm pin and the 100 mm pin was considered linear and likely be four times larger.

The relation to other tests methods detailed in Fig. 3 suggest that the CIH showed the best correlation with the shear tester with the 100 mm pin on natural soil pitches. Although mere, the rest of the relationships were poorer with less relation to the 50 mm pin. The CIH is the most relatable, as the properties of clay-based pitches are more dependent on the moisture content. When moisture is low or the clay is compacted then it is harder, requiring more force to shear. The poor relation with the RTD and CIH is a positive factor as it suggests that the shear tester is measuring a property that is currently not collected by performance tests. The shear tester’s use could increase the reliability of the Scoreplay system’s ability to predict quality. Hybrid systems are currently the gold standard for stability: the Scoreplay system currently undermines this.

The overall mass applied to the surface is 110 kg with the weight of technician and shear tester. The amount of pressure currently applied to the surface is low at 6 kPa. This is a small pressure and although it did show variations in confining and unconfined soil, it should be more reflective of a player’s impact on the soil.

4.2. CONCEPT IMPROVEMENTS

The prototype was developed to provide indication of shear stability of pitches. It was designed with simplicity in mind as little was known about the apparent failure zone. This initial testing indicated a number of factors that could be improved in the prototype to produce more precise readings, which are more representative of sporting performance. The main alteration required is the mass of the arm. Weight/mass reduction is needed in order to give sensitivity of failure with the 50 mm pin, while the 100 mm pin requires greater mass on the arm to fully fail soils. Different arms might be used for the two pin lengths.

Another factor that should be considered is decreasing the size of area of the plate on the surface in order to generate a more realistic contact pressure. This modification will reflect the stability more effectively of that applied by a player during a game. In order for this to take place, the prototype needs to be modified to have an area similar to a players two feet (UK average foot size), an area of roughly 0.062 m2 supporting the 110 kg load.

5 CONCLUSION

5.1. FINDINGS

The key findings from the study were that the hybrid constructions had a greater stability than natural sports pitches. This was expected because of the addition of synthetic fibres supporting the soil and grass. The shear tester could detect the most stable pitches at 50 mm (with the 50 mm pin) and the poorer pitches at 100 mm (with the 100 mm pin). The shear tester results showed limited relation to the Scoreplay, but this was only evident when there were noticeable differences. The shear tester results also showed a minor relation to the CIH and poorer correlation to the current RTD, suggesting it displayed properties not assessed by current array of performance tests.

5.2. NEXT STEPS

Future works involve laboratory testing the shear tester in controlled soil samples to calibrate the current prototype. Once complete, the prototype can be redesigned to reduce arm weight and provide means of applying more force to the soil. In addition, the footplate area in contact with the ground will be reduced in order reflect more accurately the pressures a player’s foot generates. Further field-testing of natural and hybrid systems will be undertaken of pitches of known or expected quality.

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APPENDIX E NOVEL FIELD EQUIPMENT FOR ASSESSING THE STABILITY OF NATURAL AND HYBRID TURF (PAPER 3)

Full Reference

Anderson, F.D., Fleming, P.R., Sherratt, P.J. and Severn, K., 2018. Novel field equipment for assessing the stability of natural and hybrid turfs. Sports Engineering, pp.1-11.

Abstract

Natural turf pitches are used for many outdoor sports. Turf is a complex network of interacting organic material, soil textures and water content. Turf is susceptible to damage under large surface forces, caused by intensive player movements in rugby union and football. To assess and monitor surface stability there needs to be a reliable test method for ground staff and other stakeholders. At present, no turf stability mechanical test method exists that represents player–surface interaction, especially to represent a linear movement across the surface such as in a rugby scrummage. This paper describes the development of a novel device for assessing turf stability. Verification was undertaken in the laboratory on a variety of controlled soil samples, and during a field study. The device measurements were shown to be sensitive to the shear strength of a high clay content soil at varying water content and to the density and type of sandy soils. A programme of field data on high quality pitches suggested a large effect of the turf root reinforcement. A conceptual model of soil failure induced by the device was developed to identify the key soil variables and support experimental data interpretation.

Keywords – Natural Turf, Rootzone, Shear Instability, Sports Surfaces, Water Content

Paper type – Journal

1. INTRODUCTION

Natural turf sports pitches are commonly used at community and elite level for many sports. Variations in soil textures of the rootzone (clay/sandy) dictates the mechanical properties. It is commonly observed that clay rich turf rootzones exhibit poorer mechanical properties with increasing water content. When wetter, higher intensity player/pitch interaction ('traffic') can cause extensive turf damage, including loss of grass cover and tears (divots) in the surface [1] (Figure 1). Clay rootzones require more maintenance and enhanced drainage to increase frequency of usage. To improve pitch playability and durability, higher sand content constructions have been introduced at the elite level. The sand increases drainage, however it lacks cohesive properties and relies on interparticle frictional forces for stability under load. [1]. Surface damage from traffic needs to be minimised to reduce risk of player injury from unevenness or reduce traction [1-4].

In rugby union and football, a player's movement creates high horizontal shear forces (torsional and linear) between the boot and the surface. Inadequate surface stability has been reported in the media during elite competition [5,6]. The greatest horizontal forces are generated in the Rugby Union scrummage (8 players bound to 8 opposition players) [7–9]. A professional scrum pack can reportedly create peak horizontal engagement forces of 16.5 kN and sustain 8.3 kN of pushing force [8]. Professional players body mass has increased over the last 10 years [9], with players exceeding 120 kg suggesting player forces are increasing. Rugby players can wear boots with long studs (up to 21 mm) and mechanical traction research shows that longer studs increase the maximum horizontal resistance at the shoe-surface before the turf failure [10, 11].

Anecdotal ground staff observations indicate turf systems failures at depths of up to 100mm, often coinciding with a change of soil type or other potential plane of weakness Therefore, to support player safety, turf pitches should meet an acceptable quality, with the turf's ability to survive the forces applied to be both measured and understood. Hybrid turf (reinforced with plastic fibres) pitches and artificial turf have increased market share recently with the rationale that they are more wear resistant and stable and have been accepted at elite levels [12, 13].

The stability of the turf (shearing resistance), is thought to be influenced by a complex interacting matrix of the soil materials, plant matter and water content [1]. Mechanical tests exist for measuring the boot traction of a sport surface, however they have limitations. These tests are focussed on the near surface shearing resistance to a depth of 13 mm, the length of a standard stud, and at present no industry standard test exists for directly assessing the stability of turf system deeper into the rootzone.

Fig 1 *– Photographic evidence of natural turf system damage caused by the back row of a rugby scrum*

The aim of the study was to develop a new method to assess the shear stability of natural turf across a range of sports pitch construction types. The paper introduces the natural turf pitch structure and previous relevant studies of turf strength. It then details the new prototype device and presents data from a series of field tests and controlled laboratory experiments. A theoretical conceptual model was derived for comparison to the measurements.

1.1 TURF CONSTRUCTION AND STABILITY OF NATURAL TURF

The construction profile of natural turf can have many variations [1, 14, 15]. The grass leaf is generally cut to between 20–50 mm height depending on the sport. The grass plant is grown into a soil ‘rootzone’, a controlled growing medium (Figure 2). For general-use sports venues the rootzone is typically comprised of a surface top-dressed with sand and a native (mainly clay) subsoil material underneath (Figure 2b). Elite level sports venues typically have a 200–300 mm deep rootzone layer of a sand:clay mix (90:10 by mass) (Figure 2a) [1]. To aid drainage of surface water, a porous sand/gravel layer is installed below the rootzone and a pipe drainage network is in the subsoil (Figure 2) [1]. Turf is either grown in-situ by seeding the rootzone, or alternatively a turf system is grown at a supplier, imported and laid onto a prepared base. This latter method needs time to knit together and establish rooting depth to provide adequate stability.

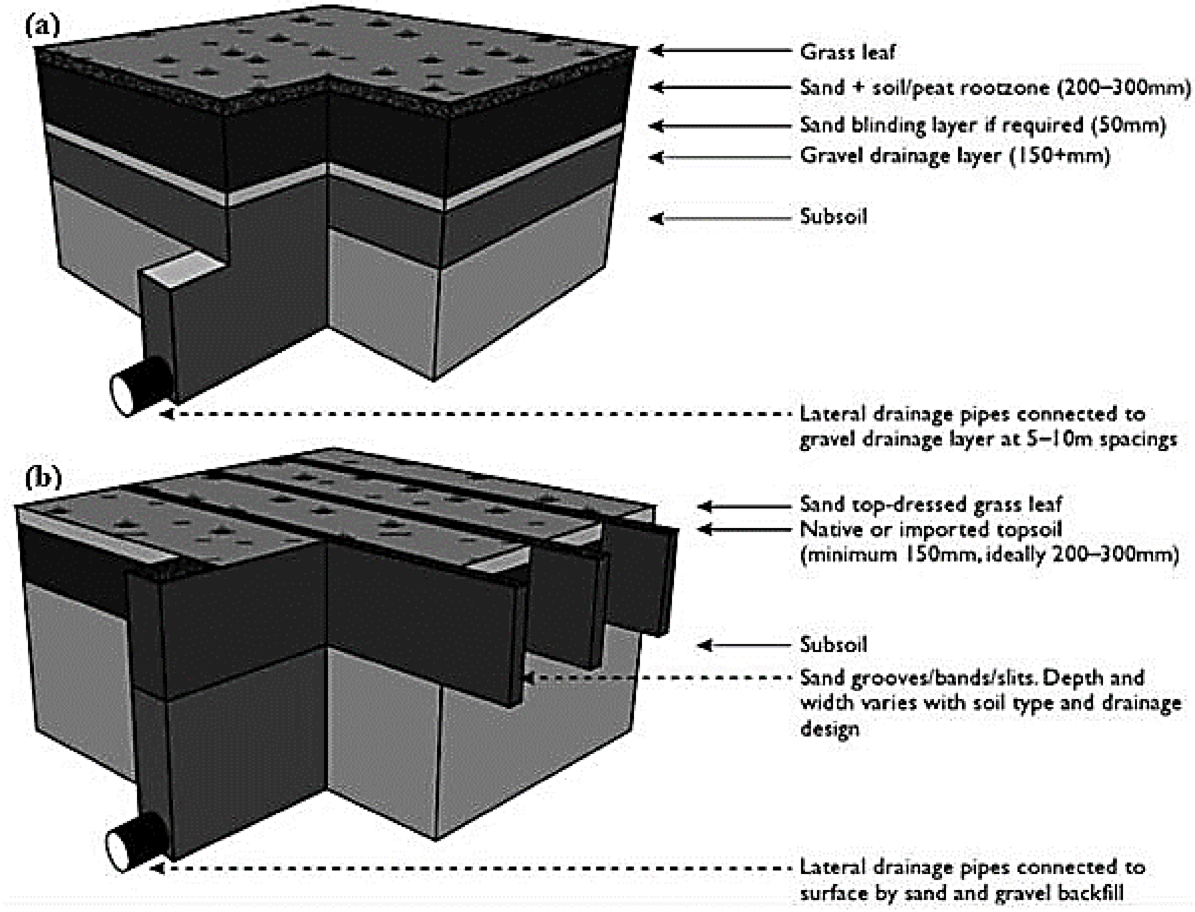

Fig 2 – A cross section of two common natural turf construction sections (a) shows a sand rootzone system common in stadiums (b) shows a sand top-dressed system with sand slits to aid rapid drainage of surface water [1]

Clay soil particles have a high surface area due to the small particle size (< 2 μm) and are chemically reactive. Clays can absorb water into their structure and hold it in tension with air suction in the pore spaces between particles [16]. Clays exhibit ‘cohesive’ properties whereby they can maintain shear strength independent of external loading [18], dependent on the initial state. High clay content in the soil system leads to low permeability at high water content the bonds between clay particles weaken, reducing its shear strength and producing plastic deformation [17].

Sand is an inert material with a larger particle size than clay (63-2000 μm) providing drainage due to the large pore sizes. The shear strength of sandy (granular) soil is derived mainly from frictional resistance between particles and is partly controlled by the magnitude of external loading and confinement. Sand exhibits no cohesive properties. Sand can also exhibit suction in the pore spaces, if well packed, whereby some strength is observed over a narrow range of water content's even under low external loading [1, 18]. An intermediate size soil, silt (2–63 μm) is also usually present with their proportions influencing the engineering and hydraulic behaviour of the soil [1]. In the agronomic industry, a soil rootzone is made of a clay: silt: sand mix to varying percentages, from clay soil (more than 40% clay), loam (clay 10-30%: silt 30-50%: sand 25-55%), to sandy soils (more than 90% sand) with a large number of iterations in between.

Previous research work has explored the key factors that influence the stability of sports turf, including: grass plant establishment, soil composition, water content and the rootzone density [3, 17, 19-23].

Laboratory investigation into the effects of soil composition was presented by Hejduk *et al*. [23]. Six different rootzone materials mixed with a medium-coarse sand were investigated, and the shear strength was observed to be greatest for the peat and compost rootzones and lowest for the sandy mix [23]. Serensits *et al*., [4] investigated the effects sand and peat mix rootzones in outdoor plots. Simulated traffic was also varied across the plots. Higher sand content rootzones were observed to be weaker, as were plots with higher simulated traffic. Higher simulated traffic caused compaction, effected grass growth and decreased strength.

Laboratory research investigated [24] to what depth a sandy clay rootzone may influence the response to (dynamic) loading caused by human subjects running across the surface. Soil pressure transducers, buried at depths of 100 mm, 200 mm and 350 mm, demonstrated the largest changes in the additional dynamic soil pressures were observed in the top 100 mm.

Grass root's influence on shear strength was investigated in Tengbeh's [25] laboratory study. Several samples of a loam and a high clay content soil were seeded. The stability of the soil /grass suggested that fully established grass root increased the strength by up to 500% relative to the bare rootzone. Other studies have similarly demonstrated roots provide increased resistance to shear, through a build-up of tensile resistance [26], and allow greater shear displacement before ultimate shear failure [27].

1.2 TURF SHEAR STRENGTH TEST DEVICES AND RESEARCH

Presently, one industry standard device exists for measuring the maximum rotational traction resistance of sport turf surfaces. Created in the 1970s' during studies assessing play performance of natural turf fields, it was implemented into routine tests in the 1990s' in national/international standards [28, 29] for artificial turf. It is referred to as 'Rotational Traction Device' (RTD) and comprises a six-studded (studs 13 mm long) cylindrical disk loaded with a 46 kg mass, a tripod for stability and a torque wrench. The disk is lifted 60 mm and dropped onto the surface to provide stud penetration. The disk is then rotated manually using the torque wrench, to measure the peak resistance when the turf surface 'fails' [29]. The mass applies a confining load to the surface during testing creating capability to test sandy soils by creating an applied force to the surface particles, locking the particles in place and increasing strength. This standard test method has an upper and lower limit of acceptability set for artificial turf based on measurements of 'good quality' natural turf. Research investigations of the apparatus have criticised it for poor inter-operator reliability [30], suggested the low normal static load is unrealistic compared with the larger vertical loads generated by athletes [11] and, that as failure occurs at large rotation angles of around 40°, the measurements do not reflect the relatively small player boot–surface rotation observed in-game [11]. Furthermore, due to the standard length (13 mm) of football studs used (also specified for rugby), it was observed that the test result is mostly influenced by the grass leaf (usually 25-40mm high) and near surface rootzone.

The Going Stick® (Turftrax Ltd, Cambridgeshire, UK) (GS) was developed to assess the firmness (‘going’) of horse race tracks, providing a quantitative monitoring tool for groundsmen. It is an instrumented small spade-like device with a flat metal tine (100 mm long x 21 mm), which is inserted vertically into the ground to a 100 mm depth and rotated through 45°. The device readout combines the measurements of resistance to vertical penetration and horizontal rotation into an ‘index’ value and is considered a relative measure of the turf stability. An investigation into the feasibility of the device for use on sports turf [31] for football/rugby showed inadequate upper measurement range of the device, despite software modification. However, a good correlation was found between the GS index value and the RTD peak torque [31] on clay soil rootzones. In contrast, however, a separate investigation [32] on elite level pitches with sandy rootzones observed low GS index values relative to clay soils and found poor correlation to peak traction measured with the RTD [32]. This study concluded that during the GS testing in sandy soils, low shear strength was measured due to the lack of surface confinement available from the device [32].

The Hand Shear Vane (HSV) is a standardised geotechnical testing method used to assess the undrained shear strength of clay materials [33], usually in the field, and has been used in previous studies on clay rich soils [25]. The device comprises a cruciform vane, which is inserted into the soil to 51 mm and rotated to the point of soil failure, the measured torque required infers a soil shear strength reading (factory correlation). However, the device is not suitable for use in granular sandy soils for the reasons of lack of confinement, similar to the GS, and large disturbance of the soil during insertion [17, 32].

The range of devices and past research reviewed demonstrates a gap in the current capability to routinely assess the (relative) shear stability of natural turf sports pitch rootzones. The devices are limited to shallow depth and/or measure under the wrong loading conditions. To evaluate the deeper failure a prototype was designed to create capability to measure the variety of soils textures under conditions more akin to a player’s vertical ground reaction force (GRF) interactions and evaluate to a depth of 100 mm in the turf root zone.

2. PROTOTYPE DESIGN

The prototype device was designed to evaluate the shear stability of a range of soil textures and hybrid turf constructions (Figure 3). The device is a mechanical test method utilising a weighted test arm to transmit a mass through a pivot point to a steel pin inserted into the soil. The weighted test arm mass is increased until the soil failure occurs. A cantilever arm reduces the increments of applied force to the pin, increasing the sensitivity of measurements to a force lesser than the test arm mass alone (17 kg). The length of the pin can be adjusted to measure stability at several depths up to 100 mm. The operator weight (80 kg throughout the study), when standing on the base plate, provides additional confining pressure to the soil underneath.

The prototype design aimed to approximate the mode of failure of a natural turf pitch from a rugby player’s boot in a scrum. The device’s test arm falls under gravity alone (Figure 3a), avoiding operator influence. Two pins lengths were used, similar in shape and width to a rugby stud [34] (20 mm diameter), of length 50 mm and 100 mm to investigate stability behaviour of the turf systems at differing depths within the rootzone.

Analysis of the player’s foot/boot movement during scrummaging [35] showed that initially the boot is horizontal with the surface. During engagement when the player pushes forward, the heel rotates upwards about the metatarsophalangeal joint (MPJ) rotating the studs, leaving only the forefoot in contact with the surface. The angle at the MPJ did not generally exceed 27° [35];

providing indication of the minimum rotational movement range the prototype should incorporate. Analysis of research into peak scrum force data (16.5 kN) [7] was combined with a study showing the front row (three players) exerted the greatest force of the scrum pack [35] to estimate horizontal forces at the boot-turf interface. Assuming the scrum forces are distributed evenly between the three front row players' legs led to estimations of average horizontal maximum forces of around 1.16 kN. The range of applied torque for the device was thus designed for above and below this average.

The total mass of the device, plus operator, was similar to the mass of a heavy rugby player (120 kg). The plate included a rectangular cut out (22 mm x 9 mm) to allow pin rotation. The confining effect was important to improve the capability to test sandy soils under conditions similar to a player's boot vertical GRF. To allow the operator to stand comfortably, the base plate has a surface area of 0.16 m^2 creating a vertical confining pressure of around 7 kPa, considered low relative to a rugby player's vertical foot pressure.

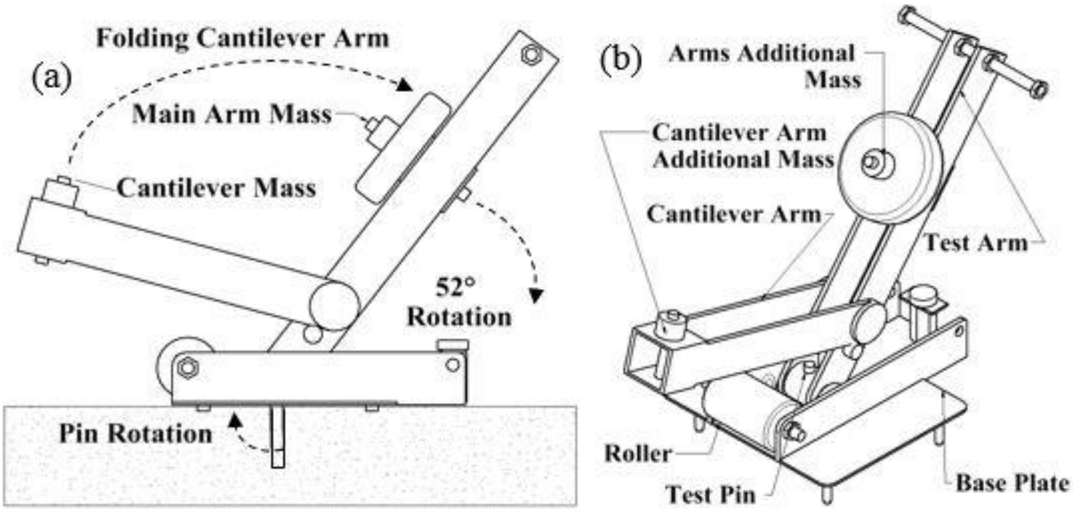

Fig 3 – A schematic of the prototype device showing the design and key moving parts in (a) and obliquely (b) The cantilever arm (9 kg) can be extended or folded in line and held in place with the main arm to bring the total arm mass to 26 kg, with capacity for additional masses

2.1 PROTOTYPE DEVICE OPERATION PROCEDURE

The procedure developed for a turf stability test comprised of three steps. Firstly, the weighted lever arm is lifted into its start position of 52° from horizontal and held in place with a quick release latch. Secondly, the test pin is then driven with a mallet vertically into the turf through the pivot hole, to the required test depth (50 or 100 mm) and secured with a grub screw. Thirdly, the operator stands on the base plate and carefully releasing the latch, allowing the test arm to fall under gravity, applying a known torque (moment) to the pin (Figure 3). If the turf and rootzone yield to the rotating pin the arm rotates until it comes to rest at the horizontal. If the turf and rootzone resist the pin force, then more weight is added to the arm until failure occurs.

2.2 PROTOTYPE DEVICE FORCES AND CONCEPTUAL SOIL FAILURE MODEL

The estimated force was calculated by balancing moments around the pivot point for the initial start position of 52° at the point the latch is released, Table 1 shows the estimated force on the pin tip for the range of masses added to the test arm (and./or cantilever arm).

The exact failure force is uncertain and is in fact a range, depending on the increments of mass applied. For example, for a mass of 10 kg on the test arm, the turf may be stable but for 15 kg mass the soil may then readily fail, therefore the specific yield force is somewhere in between. For operational simplicity 5 kg increments of mass were used. In the table, when the cantilever is used, the two masses are separated by a colon (i.e. 5:5). The first number indicates the mass on the test arm, 'test arm only' indicates the cantilever in the closed position, locked to the test arm. The pin force range that can be measured by the device meets resultant scrum player forces calculated in previous research (1.04 kN) [2]. The force range for the 50 mm pin is 187 N to 2.1 kN; and for the 100 mm pin is 117 N to 1.1 kN, respectively.

Table 1 – The range and increments of pin forces achievable by masses applied to the arm(s), showing the step changes for the 50 mm and 100 mm pin.

Mass Applied (Kg)		5:5	0	10:5	5	10	15	20	25	30
50 mm Pin	+ Cantilever (N)	187	235	375.	424	612	800	1177	1365	1554
	Test arm Only (N)	x	x	704	1059	1237	1414	1770	1947	2125
100 mm Pin	+ Cantilever (N)	117	148	236	267	385	622	741	859	978
	Test arm Only(N)	x	x	443	555	667	778	890	1002	1114

A conceptual soil failure model was developed to predict the approximate range of peak (pin) forces expected on the soil rootzones at failure and identify the effect of changes in soil type and state (i.e. density, water content and shear strength) on these failure forces.

The failure mechanism, based on the classical laws of soil mechanics [17], was considered as a simple shear failure of the block of soil in front of the pin within the arc of the pin rotation (Figure 4). The total resisting shear force was considered equal to the product of the maximum shear stress (i.e. shear strength) of the soil block and the surface area of the block. The effect of inserting the pin displacing the soil was considered negligible, though it may change the density of the soil locally.

The maximum shear stresses a sandy soil can withstand is a function of the frictional properties of the soil particles and the normal (confining) stress conditions across the failure plane [17]. Using the Mohr-Coulomb failure criteria [17] and assuming cohesion of the granular soil is 0 the equation is given as:

$$\tau f \ = \ \sigma' tan\ \varphi' \qquad (1)$$

Where τ_f is the shear stress at failure, σ' is the effective stress (stress between soil particles) and could be estimated to be the same as the total stress if it is assumed no pore water pressures occur, and φ' is the angle of friction of the soil particles estimated from laboratory shear box tests. The *horizontal* effective stress across the vertical failure planes was required (σ'_h) and can be estimated from the vertical stress in the soil using lateral earth pressure theory [17] and the relevant earth pressure coefficient(s) dependent on the angle of friction of the soil.

The peak total resisting force (F_T) can be estimated from:

$$F_T \ = \ \sigma_v' \ K_p \tan \varphi' \ (2A_S) \qquad (2)$$

where A_s is the surface area of each side of the failure wedge, K_p is the 'passive coefficient of earth pressure', and the vertical soil stress (σ_V'), the product of the self-weight of soil and the *average* depth of the failure wedge. The total vertical stress includes the vertical confining pressure provided by the apparatus base plate with the operator self-weight in place, estimated as 7 kPa. The area of the base strip of the wedge under the pin end is small relative to the total surface area of the sides of the wedge (A_s) and was ignored.

For cohesive soils (i.e. clay rich, typically > 15% by mass), it is assumed that the clay soil is close to fully saturated and the relatively rapid rate of shearing (recorded as one or two seconds) mobilises the *undrained* shear strength [18]. The soil strength in the undrained state is given the term *Su* for *undrained*. The effective angle of friction during undrained loading is zero, simplifying the analysis such that the Mohr–Coulomb failure equation becomes:

$$\tau f = Su \quad (3)$$

The confining pressure (P) provided by the apparatus base plate provides additional resistance to failure of the block in the form of a surcharge. In the case of cohesive soils, the total failure force (F_T) may be simply estimated from:

$$F_T = (Su + P)(2A_S) \quad (4)$$

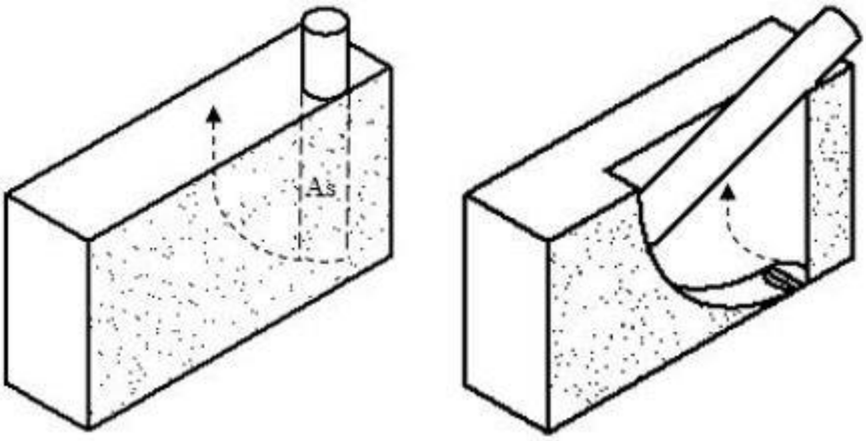

Fig 4 - Simple schematic of the conceptual model of the soil failure mechanism, showing a curved wedge failure in a block of soil in front of a pin.

3. METHODOLOGY TO VERIFY PROTOTYPE DEVICE MEASUREMENTS

A field testing programme was undertaken [3] and further laboratory testing. The key objective for the field study was to collect data across a varied range of pitch constructions used for the 2015 Rugby World Cup (RWC), contrast the data between pitch types and compare the findings to pitch play performance and agronomy tests. The competition pitches, as expected, were generally all a high standard, thus a narrow data range was observed. The pitches classified as 'sandy loam' (approximately 20% clay: less than 40% silt: 50 to70% sand), by visual inspection of the agronomists, were included in this paper to contrast to the laboratory data on sandy soils.

A programme of laboratory testing evaluated the device and its sensitivity to controlled changes in the physical soil properties, such as density, particle size range/packing and water content. The materials tested were commonly used sandy (more than 90% Sand) rootzones, termed MM45 and 80/20, a 'Fibresand' (FS) product which incorporates small plastic fibres, and a high clay content (clay 55%: silt 15%: sand 35%) fine grained soil (Fireclay) routinely used in teaching and research. Each soil type underwent testing to classify the materials and explore its behaviour relevant to interpretation of the new device and for use in the conceptual model to predict failure forces. The materials testing followed British Standards (BS) for particle size distribution (PSD) [36], compaction behaviour to determine the optimal dry density [36] and sensitivity to water content. The MM45 and FS also underwent shear box testing [24] to measure the angle of friction of the soil to evaluate shear strength. The compacted Fireclay samples were tested to evaluate the undrained shear strength using the HSV [24]. Target values for sample water content were selected based on the compaction curve data and field observations (Figure 5 and 6) to give relative values for low, medium and high.

The samples were brought to the target gravimetric water content by mixing the correct ratio of water mass and dry material mass into a Z-blade mixer. The prepared soil samples were placed into a box container for testing (500 mm x 300 mm x 200 mm) and compacted with a Kango

950 X electric vibrating hammer in three layers of consistent depth to create a uniform density. Prototype device testing locations avoided the potential confining effects of the container walls or influence of other test locations, in three positions with the 50mm or 100 mm pin. After testing, a sample of the top 100 mm of soil was removed and dried to determine the gravimetric water content, bulk and dry density, and air void content.

4. RESULTS

4.1. SOIL PHYSICAL CHARACTERISTICS

The compaction curves in Figures 5 and 6 show the relationship of dry density against gravimetric water content and air void content (for the same full-face compactive effort into steel moulds). The box samples' dry density (shown as single data points) could be compared to the compaction curve demonstrating lower density and higher air voids were achieved than in the BS tests, due to the unconfined nature of the box. Figure 5 demonstrates that for the sandy soils a change in water content had little effect on the resulting dry density in the standard compaction tests. MM45 gave the lowest dry density and to achieve full saturation (0% air content) the data suggests gravimetric water content greater than 20% was required, however, the observations during compaction were that water drained from the samples at the higher water content showing this extreme was not achievable. The Fireclay compaction curve (Figure 6) showed the expected relationship with more sensitivity of dry density to changes in water content, relative to the sand, and an optimum water content of around 13% to achieve the maximum dry density. At water content above 14% the air void content was estimated to be close to 0% showing the Fireclay was close to full saturation and well compacted. The box samples' dry density, when compared to the BS compaction curve, show good compaction achieved at water content close to the optimum but high air voids at increasing water content.

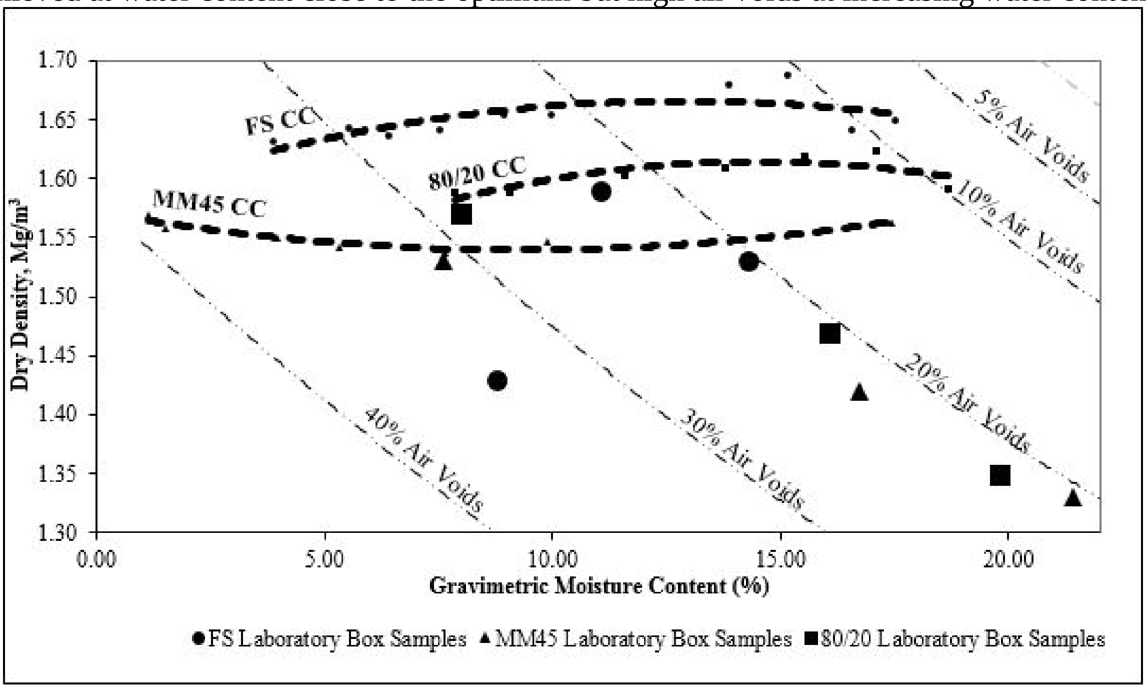

Fig 5 – A diagram to show the relationship between dry density, compaction curve and air void content for the three sandy soil materials, from standard compaction tests, indicated with the compaction curve (CC) trend lines. Included are data points showing the density state and gravimetric water content of the compacted box samples tested with the prototype device

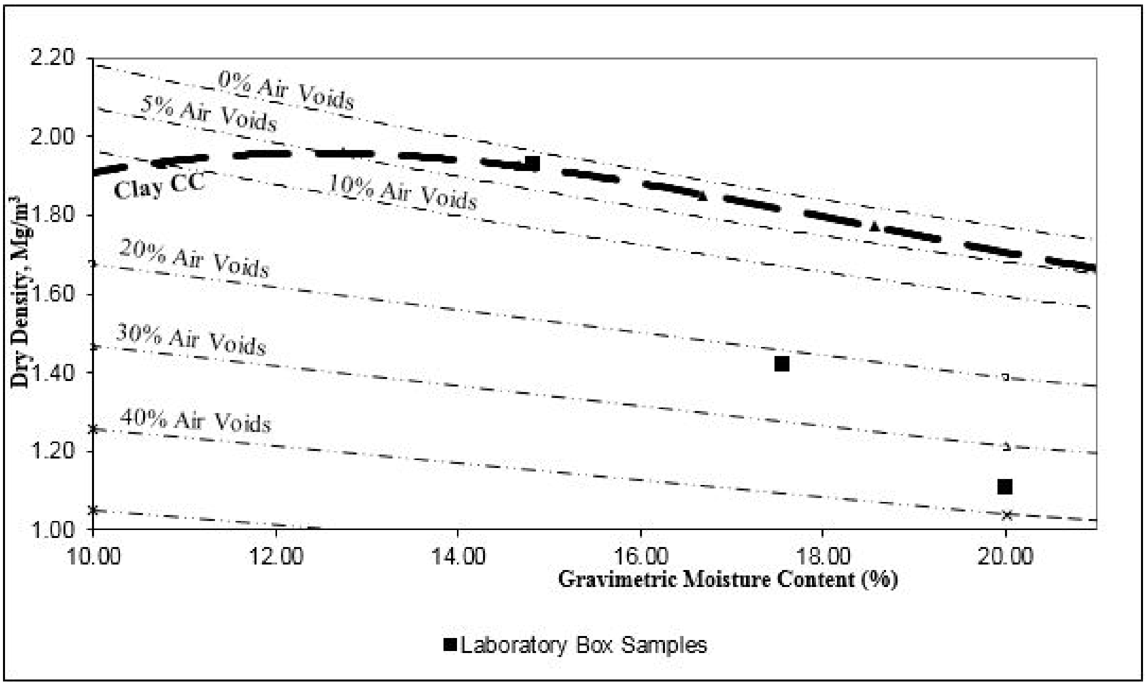

Fig 6 – A diagram to show the relationship between dry density, water content and air void content for the Fireclay material, from standard compaction tests, indicated with the compaction curve (CC) trend lines. Included are data points showing the density state and gravimetric water content of the compacted box samples tested with the prototype device

The HSV results of the undrained shear strength (S_u) for the compacted Fireclay samples were 204 kPa, 156 kPa and 64 kPa at 14.8%, 17.5% and 20% gravimetric water content respectively. The HSV gave relative values for comparison to the new device, despite some accuracy limitations [17].

Shear box testing measured the angle of friction for the MM45 and FS samples, at three normal stresses of 10, 25 and 50 kPa, at two densities (1.2-1.6 Mg/m^3) and two gravimetric water contents (8 and 17.5%) to represent the range observed in the box samples. In general, water content showed little effect; however, density showed a large relative effect on the angle of friction, especially for the FS (50-58°) which displayed larger magnitude values than the MM45 (42-48°).

4.2 PROTOTYPE DEVICE RESULTS

The laboratory and field results from the RWC sandy loam constructions are presented in Figure 7 and 8 for the 50 mm and 100 mm pins, respectively. The field results, as represented by RWC, gave higher failure forces than the laboratory sand samples. The comparison is somewhat subjective with higher stability perhaps largely due to the presence of grass root reinforcement in the field, and the field rootzone density is unknown. Water content had little effect on the failure forces observed for the sandy materials in the laboratory and field. However, the FS showed some effect of water. Water content changes for the laboratory Fireclay samples showed a strong relationship of reducing pin failure force with increasing water content, however, increased air voids and reduced density also led to lower failure force (Figure 7 and 8). In addition, as expected, the device results for the 100 mm pin show higher failure forces than for the 50 mm pin in all the laboratory samples and field data.

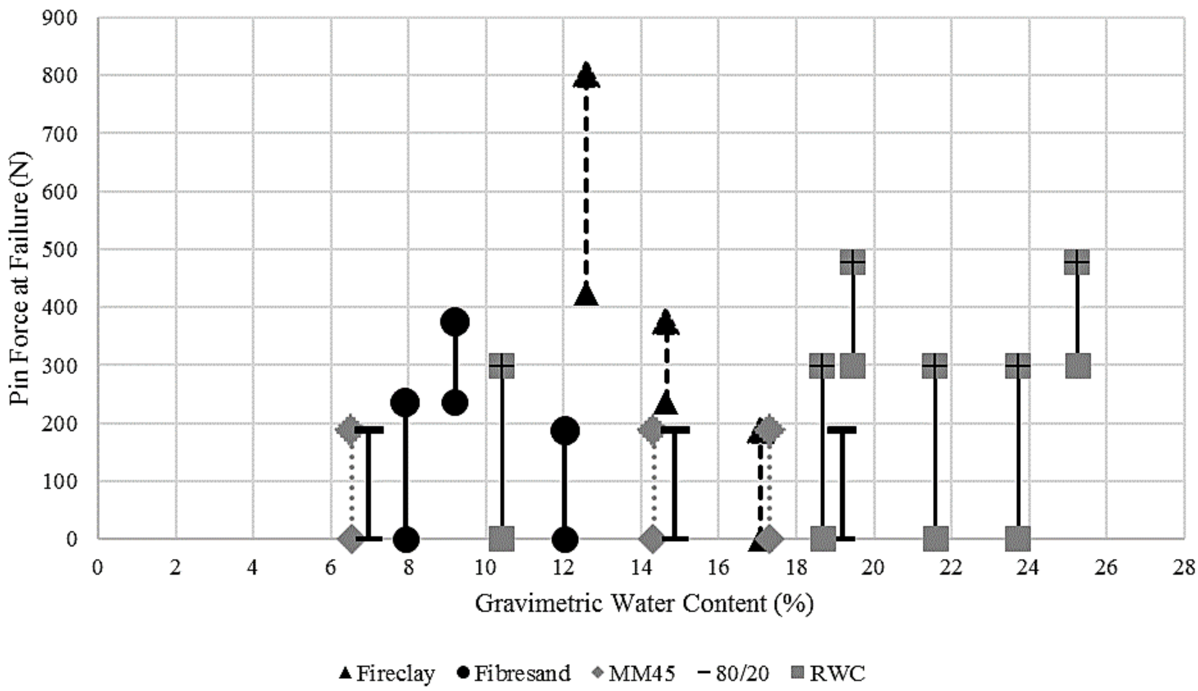

Fig 7 – Laboratory and RWC sample gravimetric water content compared with the 50 mm pin force range at failure

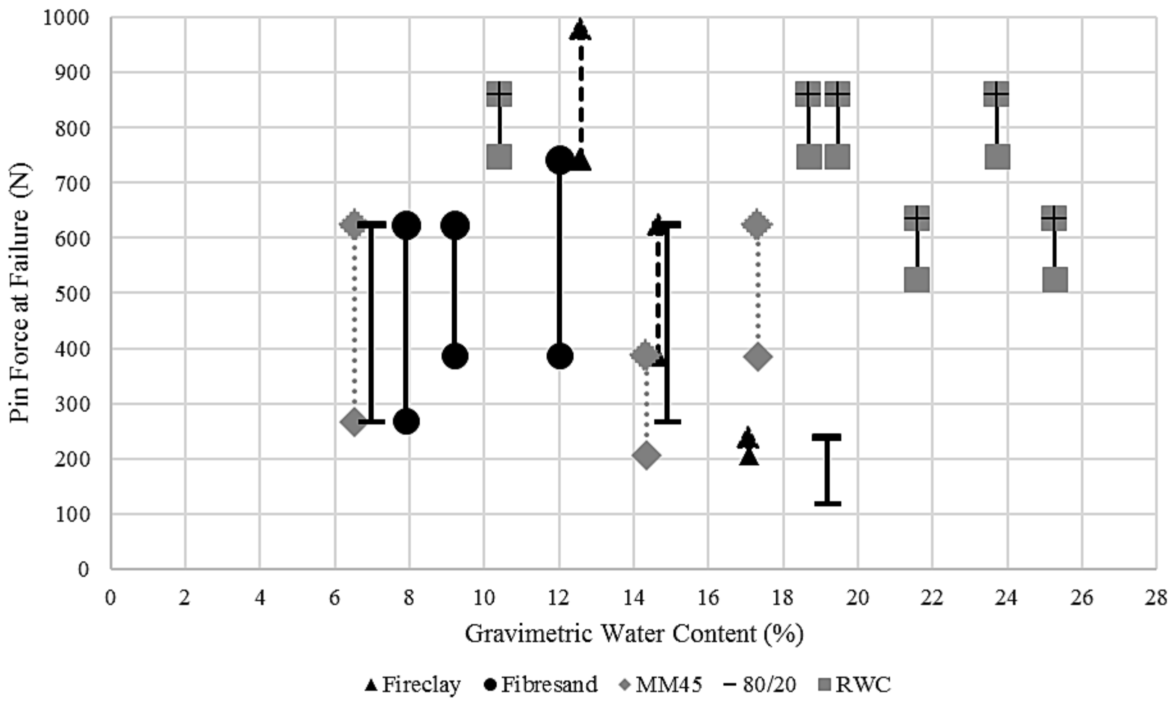

***Fig 8** - Laboratory and RWC sample gravimetric water content compared with the 100 mm pin force range at failure*

The mode of failure observed in the laboratory box tests for the different materials was visually assessed (see Figure 9). The shape of the permanent damage caused by the pin was observed to be similar for all four materials, with little disturbance to either side at the surface, typical of a plastic cohesive soil shearing without volume change [17] similar to that proposed in the conceptual model for the clay. For the sandy soils this observation suggests more compression during shear, rather than the block failure proposed in the model, due to the low bulk density of the samples (air void content more than 20%).

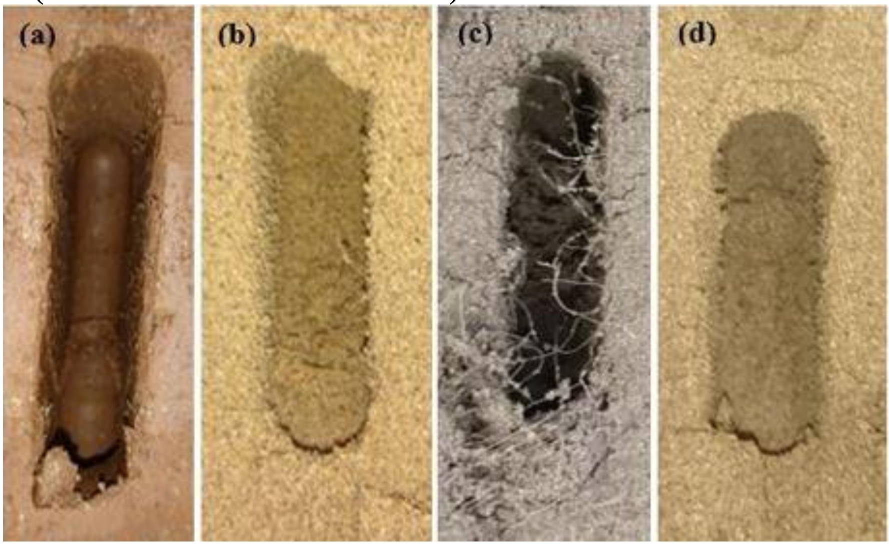

Fig 9 - *Examples of the failure zones observed after pin removal in all samples. (a) 100 mm pin Fireclay failure zone at 15% gravimetric water content (b) 100 mm pin MM45 failure at 8% gravimetric water content (c) 50 mm pin FS failure at 8% gravimetric water content: (d) 50 mm pin 80/20 sand failure at 8% gravimetric water content.*

5. DISCUSSION

The prototype device was designed and manufactured to provide assessment of shear stability of turf across a range of construction types to a depth of up to 100 mm. To validate the device, a range of soil textures with varying density and water content states were tested and evaluated.

5.1 MATERIAL BEHAVIOUR AND PROTOTYPE DEVICE RESULTS

The prototype device showed sensitivity to the compacted state and water content of the clay soil, in accordance with universal principles of soil mechanics. However, the prototype device was observed to be more sensitive to the changes in water content than the HSV.

For the sandy soils the 50 mm and 100 mm pin results showed little effect of water content, except for the FS. With the 50 mm pin, FS demonstrated an interesting trend whereby an increase from low to medium water content increased the resistance to shearing, except for the highest water content where the shear resistance reduced. In contrast, the 100 mm pin resistance showed a continued increase with increased water content. The FS has a higher percentage fine sand content than the MM45, which produced slightly better particle packing demonstrated in the higher compacted densities (Figure 5), and greater relative shear resistance as observed in both the prototype device and laboratory shear box test results (see Table 2). Furthermore, the device results showed little relationship with the compacted density of the MM45 and 80/20, in contrast to the shear box results and the clay. However, this may be due to the relatively low confining pressure compared to the shear box. However, more sensitivity to the soil state was shown by the 100 mm pin than the 50 mm pin.

The RWC turf fields produced higher resistance to shearing with the pins than most samples in the laboratory, regardless of water content, as might be expected through reinforcement by the grass plant. However, in the RWC testing program it was not possible to measure in-situ density or water content accurately. Further fieldwork has incorporated standard in-situ cores (44 mm diameter, 200 mm deep) [37] for density and gravimetric water content measurement to improve data quality. The RWC fields tested were also rated by agronomic tests, not reported herein, as ‘high quality’ and serve as a useful benchmark to contrast to the laboratory results.

5.2 COMPARISON OF LABORATORY TEST RESULTS WITH THE SOIL FAILURE MODEL

The laboratory experimental data was compared to the simple soil failure model predictions. Table 2 illustrates the effect on predicted soil failure force of the important properties of the soil rootzone including soil density, soil angle of friction (from the shear box tests), and the effect of the vertical confining pressure provided by the plate. The horizontal stresses (lateral earth pressure) has a very large effect, influenced directly by the magnitude of the lateral earth pressure coefficient used (K_p), which is further dependent on the angle of friction of the soil. However, the soil failure zones observed around the pin (Figure 9) suggested limited passive failure of the soil thus it seems appropriate to utilise a lateral earth pressure coefficient somewhere between K_o (earth pressure coefficient at rest [17]) and K_p. The lateral earth pressure coefficient at 'rest', K_o, is utilised in geotechnical design for conditions of equilibrium with no vertical or horizontal strains occurring [17]. Table 2 further illustrates the range of results for the predicted pin failure force for these different coefficients of lateral earth pressure. The laboratory experimental data from the prototype device showed increased resistance for the 100 mm pin relative to the 50mmm pin, by a factor of around 3–4, and matched the model predictions of a factor of approximately 3-5 reasonably well for the sandy soils. Predicted failure forces in Table 2 can be compared with the measured values in Figures 7 and Figure 8.

Table 2 – Predicted Pin Failure Forces using a simple soil failure model for sandy soils

	Pin length (mm)	Soil density (kg/m^3)	W/C (% Grav)	φ′ (°)	K_o (1-sin φ′)	Eq. 3 K_p	σ'v_{ave} (KPa)	Predicted Pin Failure Forces (N) K_o	K_p
MM45	50	1200	8	37	0.40	4.02	0.32	12.08	122.01
	50	1500	8	45	0.29	5.83	0.40	11.92	237.13
	100	1500	8	39	0.37	4.40	0.79	43.99	521.59
	100	1500	8	45	0.29	5.83	0.79	42.92	854.09
FS	50	1200	17.5	47	0.27	6.44	0.35	11.64	279.22
	50	1500	17.5	58	0.15	12.16	0.43	9.94	795.36
	100	1200	17.5	58	0.15	12.16	0.69	35.16	2814.44
	100	1500	17.5	58	0.15	12.16	0.86	35.95	2877.71

For the clay soil experimental data, the observed increase in resistance due to increased pin length was a factor of around 2, much lower than the theory-predicted ratio of around 3-4. However, the model assumes fully saturated soil, and fully undrained behaviour. Similar to the sandy soils, the presence of air voids in the clay sample is expected to change the mode of failure from plastic yield of the block to partly compression and then plastic yield, reducing the overall strength of the soil and hence reducing the resistance to shearing. The simple soil model greatly over-predicts the observed failure force by a factor of up to three, and further refinement is required to better match the postulated failure mechanism.

5.3 EVALUATION OF THE PROTOTYPE DEVICE

The field and laboratory data suggest that the relative magnitude of the pin force at failure may be a practicable way to differentiate between the stability of the rootzone for a range of natural

turf sports fields at depths up to 100 mm. However, to date no corroboration with observed turf failures of sports fields during play has been possible.
The study findings suggest the device can be used to measure relative shear stability of a range of rootzone types, from clayey soils to very sandy soils, and can show some sensitivity to the state of these soils (most pronounced for the clay with changes in water content). The soils tested represent a broad range, typical of what is found at elite level stadia through to community facilities.
The prototype device incorporates pins of different lengths to determine the yield characteristics of the rootzone at depths greater than currently possible with any standard testing methods available. The confining effect of the base plate enhances sensitivity to the yield behaviour of sandy soils, an improvement over several test methods trialled in sandy soils. However, more confinement may increase the sensitivity to variation in state.
The observed modes of failure during rugby and football games have suggested both shallow and deeper failures occur in the turf /rootzone and consequently both pin lengths will continue to be used. Continuation of field data measurements across a range of in-service pitch types will provide opportunity to further benchmark acceptable levels of shear resistance, enhanced by comparisons to other agronomic indicators of pitch quality such as turf and root quality.

6. CONCLUSIONS

Shear failure of well-maintained turf, although infrequent, is of concern to the industry. The prototype device has been developed to provide a measure of the shear stability of natural grass sports turf rootzones to depths of up to 100 mm to address this problem.
The prototype device has undergone evaluation through a programme of laboratory tests. The device accurately presented the clay soils shear resistance was highly sensitive to water content and density changes. The sandy soil’s shear was unaffected by changes in water content. The sandy soil’s 50 mm pin results are not as sensitive to the soil state as the 100 mm. The FS soil, with PP fibres present throughout, showed improved shear resistance compared to the sandy soils.
Relative to field testing on turfed elite level pitches the laboratory (unturfed) sandy samples gave lower resistance at failure by a factor of around two or greater, in broad agreement with previous research on the added benefit of the reinforcing effects of grass roots.
Larger magnitude failure forces were observed for the longer pin length, as expected. For the laboratory sandy soils, the size of differences observed was similar to that expected using simple soil mechanics theory. However, the experimental data was lower than that predicted from the simple model. The model requires refinement to capture the failure mode of low density soils and partial saturation.

ACKNOWLEDGMENTS

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APPENDIX F SOIL LABOROTORY SAND CONFINEMENT TESTING STUDY

1.0 BACKGROUND

The trial study tested the MK I device and found that its range could not test the strongest and weakest sports turf. After modifications the MK II device was manufactured with a cantilever attached to the arm to allow a greater sensitivity or force in assessing the surfaces. Further assessment of soils (not discussed in Paper 3) were also undertaken with the HP device.

In to greater understanding of product functionality, the MK II and HP undertook a validation process through lab testing. This investigated the effects of confinement on the base plate of the devices in sandy soil to establish their influence on soil.

2.0 OBJECTIVE

The study investigated the confining pressure underneath the MK II and HP devices and whether the design produces a predictable confinement to the test zone in sandy soils.

3.0 METHODOLOGY

A box was made to dimensions in order that the baseplates for the MK II and HP devices could fit on top of the sandy soil. The material used was 80/20 (sand: fine 8 % medium 69 % coarse 23 %

1. The soils were brought to water content level decided by the results of prior compaction curve testing on the rootzones. The material was placed in small 5kg batches into a Z-blade mixer, with the required water mixing to produce the correct gravimetric water content.
2. The box was filled with a known amount of material to achieve target water contents of 4 %, 7 % and 10 % gravimetric water content, and a target density of 1.4 g/cm^3 (mean density from *in-situ* testing). The water contents were chosen as Paper 3 results showed water had limited effect on the strength of results, but the chosen values might be influenced by 'apparent cohesion'.
3. Before the box material was assessed at different water contents the box was covered, weight applied to the surface and the sand was allowed to settle for roughly 24 hours.
4. Each device was tested two times at each water content. The confining pressure were 7 kPa (current pressure), 50 kPa (like rugby player foot forces) and 100 kPa (higher range). These two tests enabled the soil around each test zone to be undisturbed by prior testing.
5. A rig over the box had a pneumatic jack attached (Figure 1) and was measured by a proving ring (50 kN). Steel bars were placed on the footplate of the MK II and HP devices, equal to operator weight (80 kg) and when pressure was applied from the jack, they pushed compression force into the plate.
   The compression force for the jack was calculated by the required plate pressure the area of the footplate (Equation 1).

$$\textit{Compression Force} = \textit{Plate Pressure} \,.\, \textit{Plate Area} \qquad \textbf{Equation 1}$$

Figure 1 – The steel frame around the rig and the jack which applies the pressure to the sandy soil

APPENDIX G GRASS PLANT ESTABLISHMENT STUDY

1.0 BACKGROUND

The MK II device was validated by the laboratory study and proved to be sufficient in assessing shear stability (Paper 3). Therefore, investigation explored the affect grass plant has on shear stability. This was undertaken at a turf farm by measuring a variety of controlled turf plots constructions as grass plant grew into them over a 18 month period.

2.0 OBJECTIVES

The objectives were to compare the shear tester results against the grass establishment and determine the differences in shear stability between the construction types. The study also investigated comparisons (if any) between the field and lab results (i.e the effect grass has on the soil construction) and to better determine the failure zone of the turf from the study results. The results from the MK II were compared against agronomic tests (TDR probe and Corer).

3.0 METHODOLOGY

3.1 EXPERIMENTATION

There were six plots in total. Plots were created with a number of different soil constructions of 80/20 rootzone and native, Fibresand™, The Motz Group© (Eclipse™ and Hero™) and Mixto s.r.l. Mixto™. Seeding using a perennial ryegrass was the same across all the plots. The plots were liquid fertilised ever three weeks and had three applications of granular fertiliser during their establishment. The grass was cut (to 20 mm) three times a week and a boom irrigated the grass, running day and night in summer and when required during low rainfall.
Figure 1, 2 and 3 show the overview of the plots, and their construction.

1. The plots were visited thirteen times over the 18 months study. Most of the intervals were evenly spaced in the summer months and reducing over the winter.
2. Each plot was tested in ten (1 m x 2.4 m) different strip locations during each visit. During the first ten visits the turf surface was previously untested. The shear tester was tested alongside other performance and agronomy tests which are stated in more detail in the data analysis section later in the text.
3. The results were recorded and calculated each visit and inserted into an excel document to build understanding of the plots after the thirteen visits through the 18-month period.

Figure 1 – Plots on first day of construction

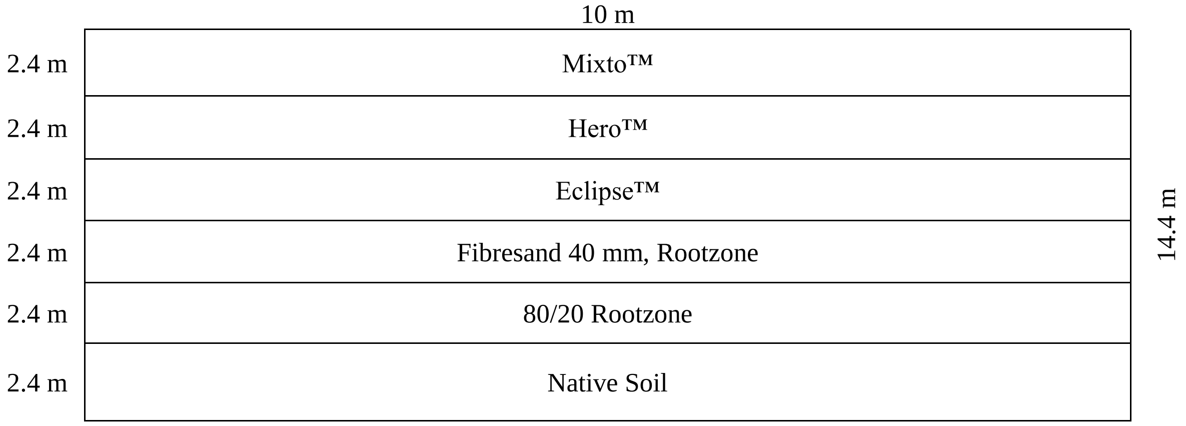

Figure 2 - Plot Elevation View of Construction and Dimensions

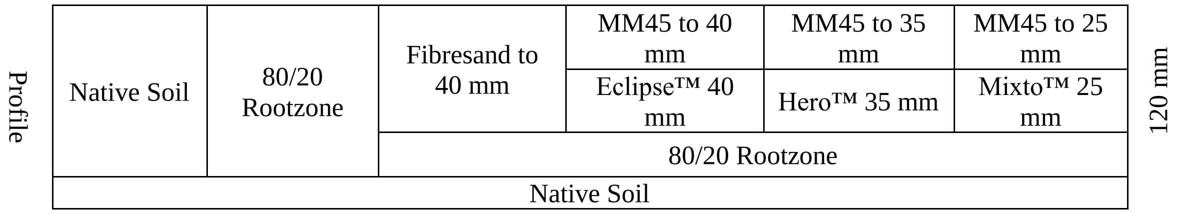

Figure 3 – Side Profile of Turf Constructions

3.2 DATA COLLECTION

During each test session, on each construction, data was collected in an area 2.4 m by 1 m. The tests allocated in these areas were observed unless there was significance difference over the plot area (i.e. patchy grass, uneven surface) (Figure 4). Specific tests had more positions depending on the quality of their data collection (Table 1). Agronomic data was collected for coverage, grass length, effective and maximum root zone. Three cores were taken to assess gravimetric water content, density and air voids. The performance tests undertaken were the Shear Tester with a 50 mm and 100 mm pin, the AAA, CIH and RTD. Water content was also taken with a TDR probe (top 50 mm) at each Shear Tester, AAA test, and core test zones.
Note: The performance data was excluded from the thesis as the shear stability was the topic of the thesis. As Section 5.6.3 details the data collected will be included in a research paper.

Table 1 - Test abbreviations and position numbers

Key	Abbreviation	Number of Tests		Abbreviation	Number of Tests
Soil Temperature	T°	1	Core	C	3
Prism Gauge	Pr	4	Moisture (Surface)	Ms	18
AAA	AAA	3	Moisture at 200 mm	Md	3
Shear Tester 50 mm	T50	4	Shear Tester 100 mm	T100	4
Traction	Tr	5	Clegg Hammer	Ch	15

2.4 meters

<table>
<tr><td>T°</td><td>(1)Pr</td><td>(5)Ch</td><td></td><td>(2)Tr</td><td colspan="2">(1)T100 & Ms</td><td colspan="2">(2)C, Ms & Md</td><td>(12)Ch</td><td>(13)Ch</td><td></td></tr>
<tr><td>(1)Ch</td><td colspan="2" rowspan="2">(1)AAA & Ms</td><td colspan="2">(1)T50 & Ms</td><td colspan="2">(2)T100 & Ms</td><td></td><td>(4)Pr</td><td colspan="2" rowspan="2">(3)AAA & Ms</td><td>(14)Ch</td></tr>
<tr><td>(2)Ch</td><td colspan="2">(2)T50 & Ms</td><td colspan="2">(3)T100 & Ms</td><td>(3)Tr</td><td>(11)Ch</td><td>(15)Ch</td></tr>
<tr><td>(2)Pr</td><td>(3)Ch</td><td>(4)Ch</td><td colspan="2">(3)T50 & Ms</td><td colspan="2">(4)T100 & Ms</td><td colspan="2" rowspan="2">(2)AAA & Ms</td><td>(10)Ch</td><td>(4)Tr</td><td>(4)Ms</td></tr>
<tr><td>(1)Ms</td><td>(1)Tr</td><td></td><td colspan="2">(4)T50 & Ms</td><td></td><td>(6)Ch</td><td>(9)Ch</td><td>(3)Ms</td><td>(5)Tr</td></tr>
<tr><td></td><td colspan="2">(1)C, Ms & Md</td><td></td><td></td><td></td><td>(3)Pr</td><td>(7)Ch</td><td>(8)Ch</td><td>(2)Ms</td><td colspan="2">(4)C, Ms & Md</td></tr>
</table>

1 Meter

Figure 4 - Grid testing during each test session

APPENDIX H SOIL WATER CONTENT STUDY

1.0 BACKGROUND

The turf farm's key investigation was to measure grass's ability to provide shear strength. However, water content was another dependent variable found to have a large affect the shear stability of turf. Therefore, a short study was conducted were water content was altered and other variables were kept similar in order to inspect water's effect on the shear instability of mid-level (common) sports pitch.

2.0 OBJECTIVE

To investigate water contents effects on shear stability, a common sports turf was wetted to saturation and dried over the course of a week. Core testing was undertaken throughout the study in all test areas to determine consistency of the plot and water contents effect on the void ratio and density. In addition to the shear tester, agronomic and sports performance tests monitored the test positions and identify if there was any variation as water contents decreased.

3.0 METHOD

Figure 1 shows the construction of the sand top-dressed football pitch (sand clay loam - clay: 28 % silt: 21 % sand: 51 % in top 150 mm depth). The plot test area was 3 m by 5 m with six test positions located within it (Figure 2). This plot was saturated and tested each 24-hour period and was left to dry out over a week.

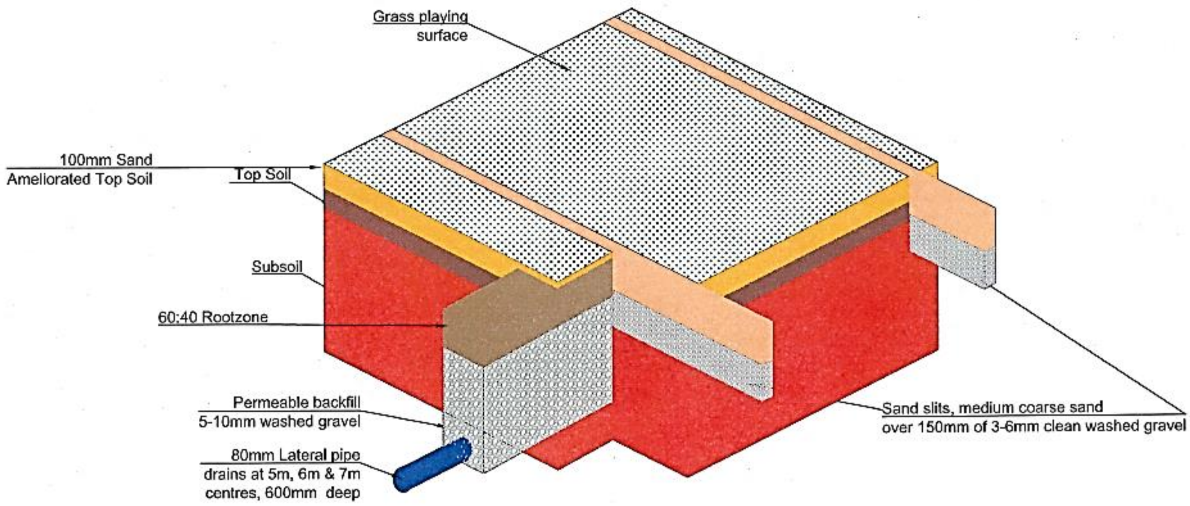

Figure 1 – Area of Plot 1 and pitch construction

1. Initial in-situ testing was undertaken using the same equipment (minus the AAA) used in the grass plant establishment study (Appendix G). A core was taken in each of the test zones (1–6) to measure the gravimetric water content, density and air voids throughout the process. The 150 mm core was split into a 50 mm depth sample and 50 mm–150 mm sample. The zones then had one CIH drop, RTD test and a single MK II Shear Test with the 50 mm and 100 mm pins. Agronomy tests of TDR probe, grass height and effective root were also taken in each location. The tests in each area was compared and averaged with the five other zones. This initial testing found the agronomic and performance results prior to saturating the pitch. During this initial test a 300 mm hole was dug. Subsoil soil samples were taken for laboratory analysis and the TDR values were taken, being repeated for each test session.

2. The day after this initial testing, the test zone was saturated with water (7 UK gallons/m^2) over the course of an hour.
3. The same tests were then repeated on the test plot after the saturation.
4. This testing was repeated every 24-hour period over the course of four days and built up a table of repeat results.

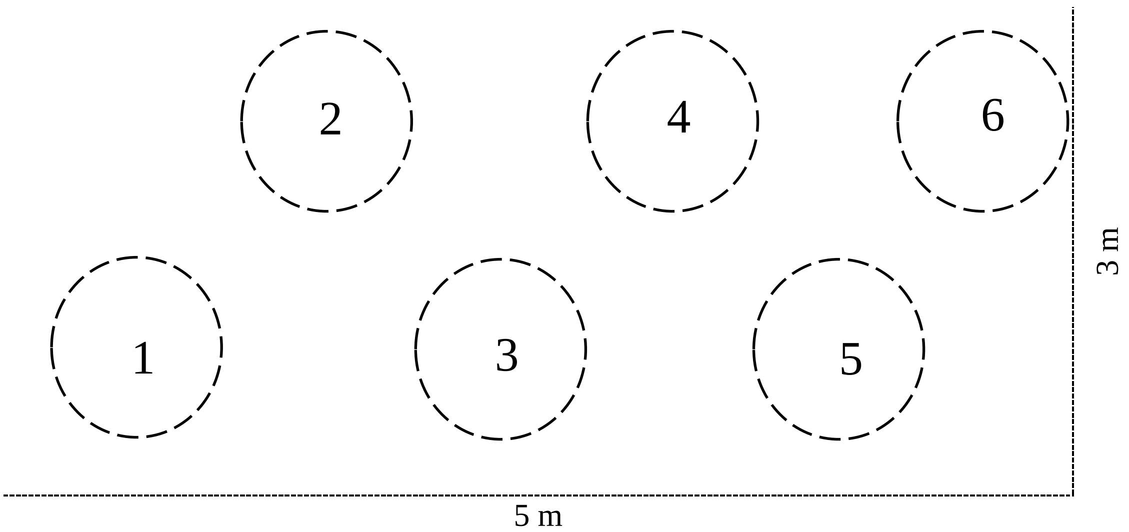

Figure 2 – Test Area and Zones

APPENDIX I STATISTICAL ANALYSIS OF AGRONOMIC AND DATA SURFACE PERFORMANCE VARIABLES

1.0 BACKGROUND

The data was collected for all the different projects (appendices E–H) over the time of the EngD. Several interesting results were found from the study, however, to truly understand the relatability of the different turf and performance devices, there was a need for further analysis both comparing the variables alone against each other and combining them against MK II results to better define relationships across all construction types.

2.0 OBJECTIVE

The objective was to use statistical tools to assess the relationships between the variables of interest on all the different construction types to assess which variables had the most effect on shear stability. This would mean that factors would need to be assessed both one to one and with several variables measured against the MK II results to distinguish relationships.

3.0 METHOD

The data was analysed with IBM® SPSS® Statistics Data Editor. The program can use a wide array of analysis techniques to determine relationships between variables. The list of variables were described in Table 1. In this methodology, the performance and agronomic data was measured both for single studies and as a whole for all experimentation (appendices E–H). Pitch construction types were combined when undergoing analysis. However, where specific variables were important, then they were also measured singularly. Two processes were used to measure the data – correlation and regression.

Before undertaking the tests, it was found that a number or the variables were skewed, meaning they were not linearly distributed and would produce incorrect results when applied to the linear models. These variables were converted to a linear scale using log (ln10) when positively skewed and reflection and log when negative.

Table 1 - Pitch constructions and the variables tested

	Variables Assessed	
Pitch Constructions	Agronomic	Performance
Native (Sandy Loam)	Bulk Density	HP 50 mm Pin
80/20 Sand	Dry Density	HP 80 mm Pin
Fibresand (Hybrid)	Effective Grass Rooting	MK II Pin100
Eclipse™ (Hybrid)	Grass Coverage	MK II Pin50
Hero™ (Hybrid)	Grass Height	
Mixto™ (Hybrid)	Gravimetric Water Content	
	Maximum Grass Rooting	
	Soil Air Void	
	Volumetric Water Content	

APPENDIX J PRODUCT DESIGN SPECIFICATION (PDS)

Table 1 – Product Design Specification of Considered Topic Factors for the Shear Tester

TOPIC

Product Need

- Is there a product that can effectively assess the shear stability of clay based, sand or hybrid sport turf? **No**

Market

- Is the market large with plenty of research and high competition? **No**
- Currently, how many products purposely s identify shear stability of sports turf? **None**
- Are there related devices that can be used to meet the needs for testing sports turf? **No, not for the wide variety of turf textures and constructions (sand and hybrid)**

Function

- How should the device operate? **The device should work on simple mechanical properties, where possible human error in the testing should be removed.**
- What outputs will the device produce? **The device should produce easy to understand testing from a simple test method.**
- Will the procedure be complex? **No, the test procedure should be simple so that anyone can use the test equipment.**

Ergonomics

- Will the device incorporate ergonomic design? **Yes, the device manufacture parameters will be designed to the UK averages**

Design

- Will the design be intricate? **No, the product will use simple mechanisms to keep prototype costs down**
- How will the mass of a rugby player be replicated? **The device will add the operators mass to create weight like a large rugby player (120 kg)**
- How will the shear strength be tested? **A pin similar in diameter to a rugby stud but exaggerated in length (up to 100 mm), will be inserted into the soil. Force will be applied to a known amount to pull the pin through the soil.**
- How will the device improve testing for all turf constructions? **A footplate will be utilised, that the operator can stand on to provide confinement to the soils adding mass and confining the surface.**

Manufacture

- What materials will be used? **The device needs to be hardy and so steel will be used for most of the device. This will ensure the device can take the high forces produced by the test pin. It will also add the mass needed to apply to the footplate and create confinement.**
- What is the lead time for the device? **The simple mechanics and structure of the device mean that the lead time will be short, 3 to 4 weeks to manufacture.**

Transport

- Will the device be portable when in transit and during testing? **Yes, the high mass of the device will be compensated with a means to transport the device via a wheel.**

APPENDIX K LABOSPORT MARK II SHEAR TESTER DEVICE STANDARDISED TEST METHODOLOGY

PRINCIPLE OF THE TEST METHOD

- The test is designed to determine the shear stability of the sports surface to depth into the turf root zone.
- A poor surface will have a low shear stability.
- The apparatus applies a force onto a pin which is vertically inserted into the surface and the peak force (N) required to initiate movement along a 52° angle is recorded.
- The test is designed for natural turf and hybrid sports surfaces; it is not suitable synthetic turf at this stage.
- The test is part of the Labosport Scoreplay™ system.

TEST METHOD

CONNECTING TO THE LAPTOP

1. Labview 10 is preloaded to the desktop with the additional configuration program, A USB cable connects the laptop to the data translation box. A 4-pin wire attaches from the data box to the potentiometer gauge located on the shear tester, which monitors the pin movement.
2. Load the software and select to record 100 data points over 5 seconds. The play button should be pressed an instant before the pin movement begins.

APPARATUS TEST PROCEDURE

1. Using the roller wheel to guide the unit, place the device at the test location on the field ensuring the base plate is flat on the surface.
2. The yellow control lever is inserted onto the control latch.
3. The arms safety catch is unscrewed to allow it to be moved into the operational test position
4. The test arm is raised into the start position (52°) and the yellow leaver is pushed towards the arm to initiate the control latch, keeping the arm in a stationary position. A cantilever arm present in the main arm can be released to counteract the force of the main arm or, if kept in place, add mass to the test arm.
5. The 50 mm or 100 mm test pin is inserted into the pivot point of the apparatus by hammering. They are hammered vertically to the correct depth as a limiter stops the pin moving deeper when it reaches its test depth.

Note: the 50 mm or 100 mm pin will be generally both used at each location, however, a measure of water content or a core visual inspection may detail use of only one pin length.

6. When in place, the operator stands on the base plate
7. The measuring software is then started on the laptop running the program.
8. The operator, while on the base plate, then instantly pulls the yellow leaver away from the arm applying force to the pin.
9. Once the arm has been released and the software has measured the failure rate (angle vs time) to 52°. Then, the data received from the potentiometer can be saved.
10. If there is no pin movement then the pin is removed from the ground, the device is moved 50 cm from the test location and the procedure is restarted, but with increased weights added to the test arm or cantilever in 5 kg increments.
11. The force (N) applied to the turf is calculated and the number of 5 kg weights on each arm can be converted to force outputs using the table below that show the turfs shear stability.

Note: The table states pin force results both when the cantilever is active and when it is part of the main arm. The two numbers separated by a colon show what weight is on each arm. For example, 5:5 means 5kg on the cantilever and 5 kg on the main test arm.

Mass Applied (kg)		5:5	0	10:5	5	10	15	20	25	30
50 mm	+ Cantilever (N)	187	235	375.	424	612	800	1177	1365	1554
	Test arm Only (N)	x	x	704	1059	1237	1414	1770	1947	2125
100 mm	+ Cantilever (N)	117	148	236	267	385	622	741	859	978
	Test arm Only(N)	x	x	443	555	667	778	890	1002	1114

12. Repeat at least three times per location, obtaining a result from the arm dropping through the 52°. The number of locations are detailed in the Scoreplay™.

	13. Calculate the average from the three tests and average the results for all the locations. Use the overall force results to apply to the Scoreplay™ rating for shear stability.			
TEST VALUES	Scoreplay™ Score*	50 mm Force (N)	100 mm Force (N)	Comments
	1	< 327	< 555	A very poor value: serious concerns for pitch stability
	2	327–424	555–779	A poor value: concerns to be raised on pitch stability
	3	424–801	779–1003	A good value: pitch stability appears strong
	4	801–1177	1003–1299	A very good value: pitch stability is excellent
COMMENTS	* Scoreplay™ ranking are based on a database of natural, reinforced, carpet hybrid and injected synthetic constructions			

APPENDIX L THE DETERMINATION OF SHEAR RESISTANCE FOR SPORTS SURFACE – HAND PULL SHEAR TESTER METHOD STATEMENT

<table>
<tr><td>PRINCIPLE OF THE TEST METHOD</td><td colspan="3">• The test is designed to determine the shear stability of the sports surface by providing a torque at failure.
• A poor surface will have a low shear stability and a good surface will have a high shear stability.
• The apparatus applies a force onto a pin which is inserted into the surface and the peak force (N) required to initiate movement along a 45°angle is recorded.
• The test is designed for natural and hybrid sports turf surfaces, it is not suitable for synthetic turf at this stage.
• The test is part of the Labosport Scoreplay™ system.</td></tr>
<tr><td>TEST METHOD</td><td colspan="3">1. Place the base at the test location on the field.
2. Apply force downwards on the base plate to ensure a base plate is flat on the surface.
3. Set the depth for the pin at 50 mm
Note: Other pin depths can be used following agronomic inspection of the soil/core profile, but these results will not be directly comparable to the 50 mm pin. The test should be more than 50 mm below the surface otherwise these systems have an unrealistic result.
4. Hammer/force the pin vertically into the ground to the set depth and lock it in place.
6. Stand on the base plate and attach the torque wrench.
7. Position the torque wrench in front of the operator at 45 ± 3˚from horizontal.
8. Pull the torque wrench for between 0.8 and 1.2 seconds from the start location through 30˚. It is important it is not pulled past 45˚; if this occurs the soil will confine under the baseplate and give an error in the rootzone shear stability value.
Note: the speed of ~ 1 second for the pull distance is important, pulling too fast or slow may result in higher or lower peak values.
10.Record the peak force in newton meters (Nm)
11.Repeat at least three times per location turning the shear tester device 90 ˚ after each repeat test. The number of locations are detailed in the Scoreplay™.
12.Calculate the average from the three tests and average the results for all locations. Use the overall torque results to measure the Scoreplay™ rating for shear stability.</td></tr>
<tr><td rowspan="5">TEST VALUES</td><td>Scoreplay™ Score*</td><td>Force (Nm)</td><td>Comments</td></tr>
<tr><td>1</td><td>0–45</td><td>A very poor value: serious concerns about pitch stability</td></tr>
<tr><td>2</td><td>45–80</td><td>A poor value: concerns to be raised on pitch stability</td></tr>
<tr><td>3</td><td>80–120</td><td>A good value: pitch stability appears strong</td></tr>
<tr><td>4</td><td>120–160</td><td>A very good value: pitch stability is excellent</td></tr>
<tr><td>COMMENTS</td><td colspan="3">The shear result is sensitive to water content for certain turf constructions, and this should be measured at each test location. Depending on the soil/sand profile a few percentage points differences in water content can change results dramatically. If a localised area appears different from other test locations, consideration should be given to the test location.

* Scoreplay™ ranking are based on a database of natural, reinforced, carpet hybrid and injected synthetic constructions</td></tr>
</table>