ORIGINAL ARTICLE

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Novel field equipment for assessing the stability of natural and hybrid turfs

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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

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) dictate 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] (Fig. 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 (eight players bound to eight 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 100 mm, 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

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

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.

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.

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,

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 and 50 mm height depending on the sport. The grass plant is grown into a soil 'rootzone', a controlled growing medium (Fig. 2). For general-use sports venues, the rootzone is typically comprised a surface top-dressed with sand and a
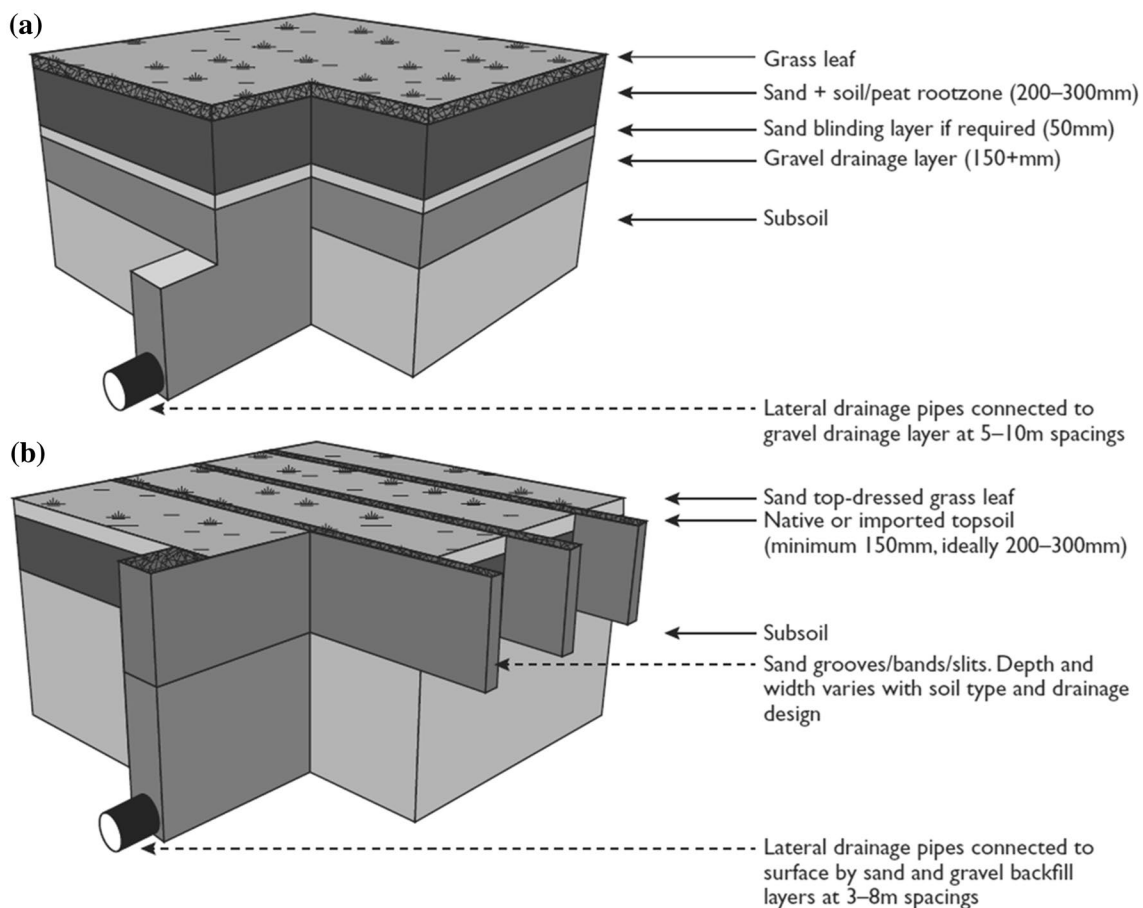

Fig. 2 A cross section of two common natural turf construction sections **a** shows a sand rootzone system common in stadiums **b** shows a sand top-dressed system with sand slits to aid rapid drainage of surface water [1]

native (mainly clay) subsoil material underneath (Fig. 2b). Elite level sports venues typically have a 200–300 mm deep rootzone layer of a sand:clay mix (90:10 by mass) (Fig. 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 (Fig. 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.

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 [17], 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, 200 and 350 mm, demonstrated the largest changes in the additional dynamic soil pressures that 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 [22].

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 [27, 28] 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' [28]. 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 a 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 [29], 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 25–40 mm 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 × 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 [30] 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 [30] on clay soil rootzones. In contrast, however, a separate investigation [31] 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 [31]. 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 [31].

The hand shear vane (HSV) is a standardised geotechnical testing method used to assess the undrained shear strength of clay materials [32], 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, 31].

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 rootzone.

2 Prototype design

The prototype device was designed to evaluate the shear stability of a range of soil textures and hybrid turf constructions (Fig. 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 (Fig. 3a), avoiding operator influence. Two pin lengths were used, similar in shape and width to a rugby stud [33] (20 mm diameter), of length 50 and 100 mm to investigate stability behaviour of the turf systems at differing depths within the rootzone.
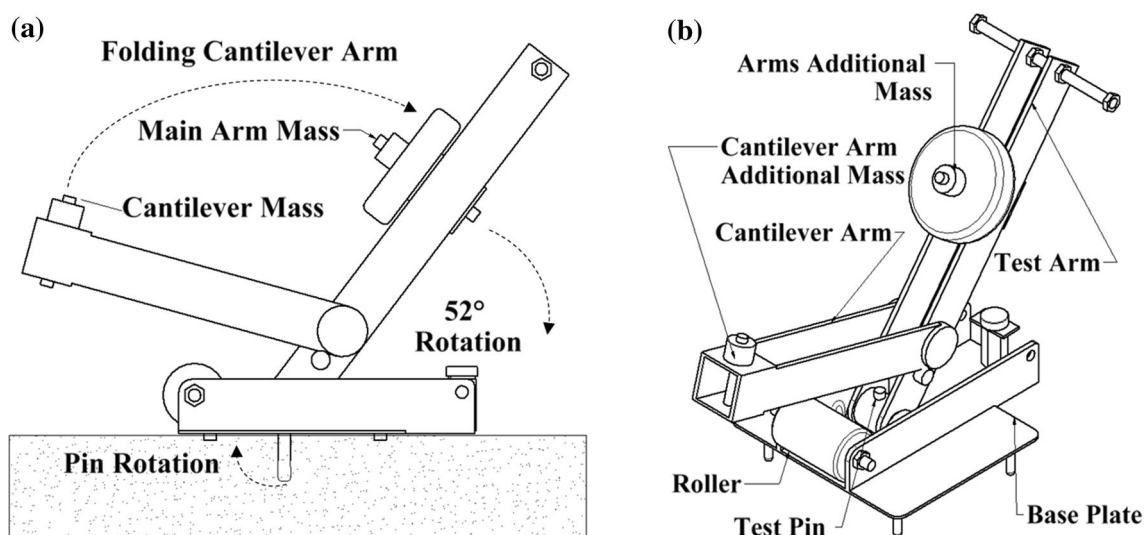

Fig. 3 A schematic of the prototype device showing the design and key moving parts in **a** and obliquely **b**. The cantilever arm (9 kg) can be extended or folded in line and held in place with the main arm to bring the total arm mass to 26 kg, with capacity for additional masses

Analysis of the player's foot/boot movement during scrummaging [34] 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° [34], 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 [34] 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 × 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 m² creating a vertical confining pressure of around 7 kPa, considered low relative to a rugby player's vertical foot pressure.

2.1 Prototype device operation procedure

The procedure developed for a turf stability test comprised three steps. First, the weighted lever arm is lifted into its start position of 52° from horizontal and held in place with a quick release latch. Second, 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. Third, 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 (Fig. 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.

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 (Fig. 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 stress, 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

$$\tau f = \sigma' \tan \varphi', \tag{1}$$

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

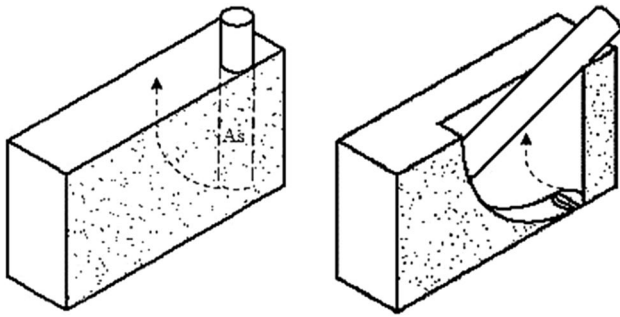| Mass applied (Kg)		5:5	0	10:5	5	10	15	20	25	30
50-mm pin	+ Cantilever (N)	187	235	375	424	612	800	1177	1365	1554
	Test arm only (N)	x	x	704	1059	1237	1414	1770	1947	2125
100-mm pin	+ Cantilever (N)	117	148	236	267	385	622	741	859	978
	Test arm only (N)	x	x	443	555	667	778	890	1002	1114

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

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 [17]. 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

$$\tau f = Su. \qquad (3)$$

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

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

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) [35], compaction behaviour to determine the optimal dry density [35] 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 (Figs. 5, 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 ($500 \times 300 \times 200$ mm) and compacted with a Kango 950× 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 50- 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.

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
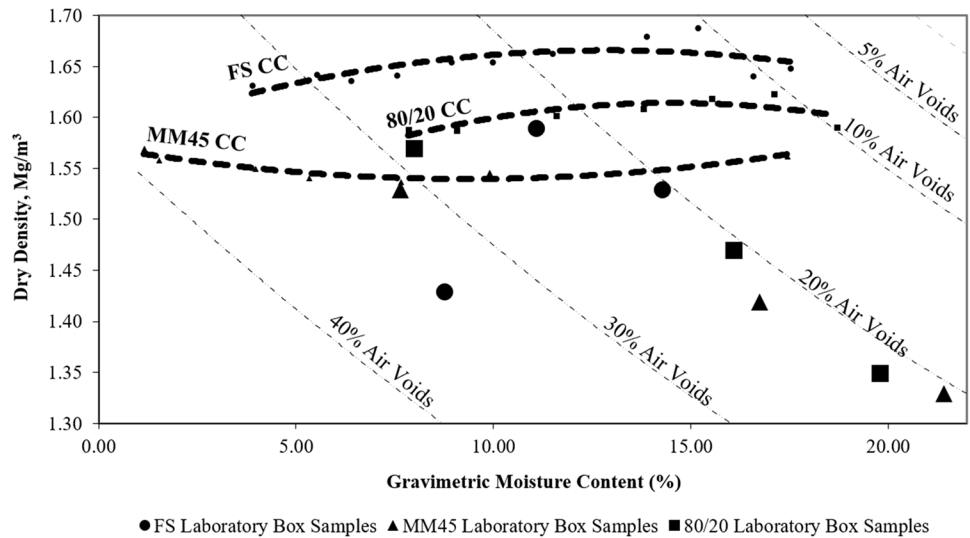
FS Laboratory Box Samples ▲ MM45 Laboratory Box Samples ■ 80/20 Laboratory Box Samples

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

■ Laboratory Box Samples
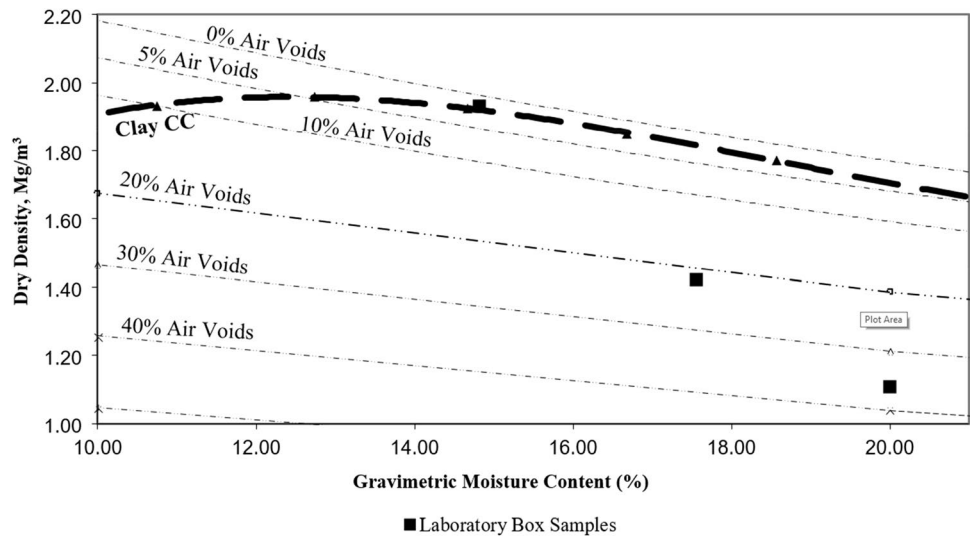
4 Results

4.1 Soil physical characteristics

The compaction curves in Figs. 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 (Fig. 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.

The HSV results of the undrained shear strength (S_u) for the compacted Fireclay samples were 204, 156 and 64 kPa at 14.8, 17.5 and 20% gravimetric water content, respectively.

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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/m³) 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 Figs. 7 and 8 for the 50- 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

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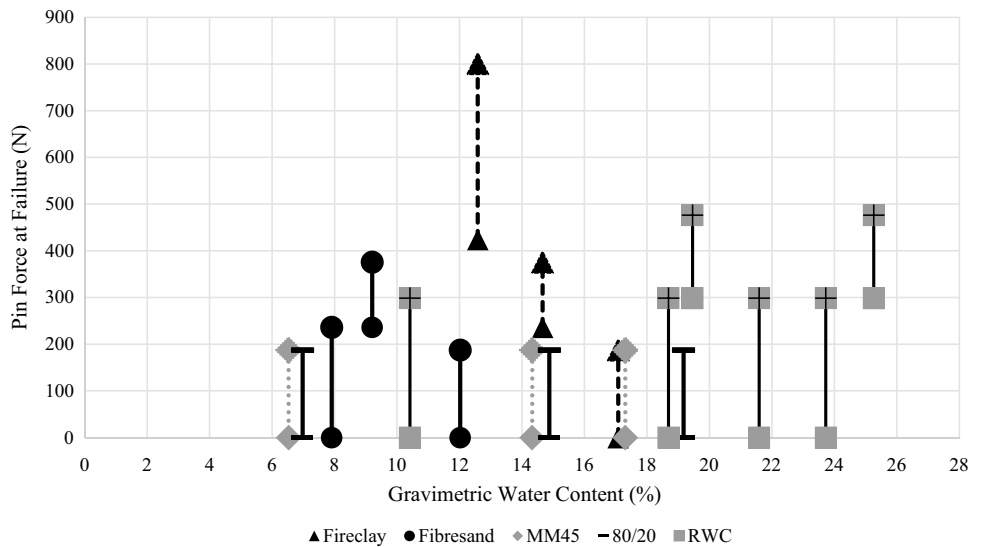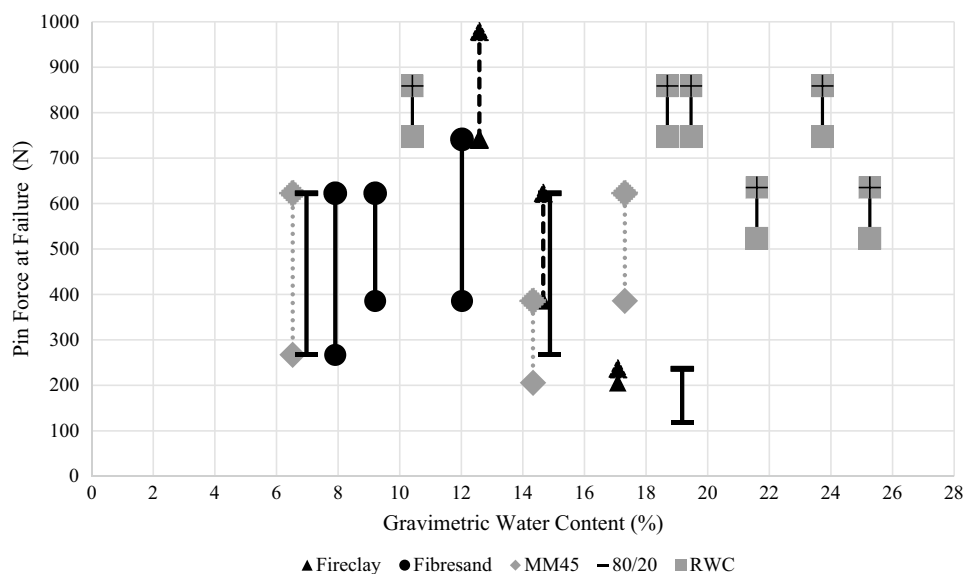

Fig. 8 Laboratory and RWC sample gravimetric water content compared with the 100-mm pin force range at failure
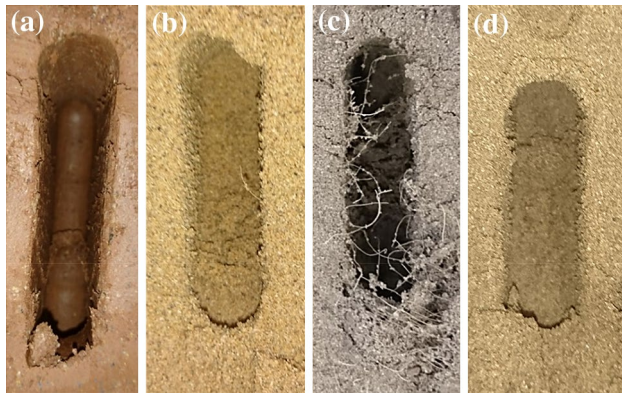
Fig. 9 Examples of the failure zones observed after pin removal in all samples. **a** 100-mm pin Fireclay failure zone at 15% gravimetric water content. **b** 100-mm pin MM45 failure at 8% gravimetric water content. **c** 50-mm pin FS failure at 8% gravimetric water content: **d** 50-mm pin 80/20 sand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

and reduced density also led to lower failure force (Figs. 7, 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.

The mode of failure observed in the laboratory box tests for the different materials was visually assessed (see Fig. 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%).

5 Discussion

The prototype device was designed and manufactured to provide the 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- 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 (Fig. 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,

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') | Equation 3 K_p | $\sigma' v_{ave}$ (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

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) [36] 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) have 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 (Fig. 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 50 mm 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 Figs. 7 and 8.

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 overpredicts 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 that 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 that the clay soil 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 were lower than that predicted from the simple model. The model requires refinement to capture the failure mode of low density soils and partial saturation.

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