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PLEASE CITE THE PUBLISHED VERSION

<http://dx.doi.org/10.1016/j.proeng.2016.06.294>

PUBLISHER

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VERSION

VoR (Version of Record)

PUBLISHER STATEMENT

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Fleming, Paul, Michael Ferrandino, and Steph Forrester. 2019. "Artificial Turf Field-a New Build Case Study". figshare. <https://hdl.handle.net/2134/22528>.



11th conference of the International Sports Engineering Association, ISEA 2016

Artificial Turf Field – A New Build Case Study

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Abstract

Artificial turf is widely used around the world and is used successfully for many sports and at many levels of performance requirement. Enhanced quality assurance systems set in place by sport governing bodies, such as World Rugby's Regulation 22 require inspection and certification of the installed system, and increasingly testing of the whole pitch build. Monitoring of play performance is then required at intervals to maintain certification for (high level) competition. However, very little published case study data exists that presents the build quality and monitoring data in a suitable form to share knowledge and best practice for the wide range of stakeholders, or for the maintenance provider. This paper presents a (unique) case study overview of the key activities undertaken and the measurement data and observations made during the construction of a full size elite level artificial (3rd generation) turf pitch, in autumn 2014 at Loughborough University. The research team monitored all the construction layers with a variety of specialist geotechnical devices, and additionally instrumented the pitch for drainage performance and thermal heat transfer. In addition play performance related properties and maintenance have been monitored during its first year of use. The test results give a unique insight into the surface system initial state and the early life changes that have occurred. The collective outcomes of the case study findings are considered useful to both academics and practitioners to further our understanding of appropriate methods of effective sports pitch monitoring for quality and performance and the expected early-life in service changes. The geotechnical measurements add to the current (global) debate on design verification and how to specify and monitor a pitch base build quality.

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Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Artificial Turf; System Behaviour; Field Testing; Quality Assurance; Construction; Temperature

1. Introduction

The construction of a full size artificial grass pitch (AGP) on the Loughborough University campus provided a unique opportunity to observe and monitor the full construction processes, and the early life play performance. Pre-contract meetings with the design and build team ensured access to the project, contract details, and safety of the monitoring team. The surface 'system' installed comprised a long-pile rubber crumb artificial turf pitch, classed as '3rd generation' (3G) [1], for use in Rugby Union and American football (section 2 includes more specific details). The construction of the AGP comprised several key (generic) steps, with inspection and monitoring at each step. The pitch foundation construction steps comprised: the excavation of the natural soils to 'formation' level; installation of the sub-formation drainage channels and pipes; and construction of the pitch sub-base comprising 'low fines' aggregate and overlain by a 'porous' asphalt. The surface sports 'system' steps comprised: construction of the shockpad; carpet laying and seaming; and infill placement and brushing. Once installed, AGPs are tested to ensure compliance with the relevant governing body play performance requirements, and to confirm that the installed product(s) match the laboratory certified samples [2]. Whilst the World Rugby [2] requirements are quite stringent regarding the requirements of the surface system, it is apparent that the design and construction guidance and quality assurance of the pitch build is often poorly specified or audited. The independent monitoring and auditing of this construction case study adds to the debate on appropriate tools and measurements for build quality, furthers the science of pitch behavior, and was vital for a well understood 'outdoor laboratory facility' to support ongoing studies into player movement and performance, and pitch modelling.

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2. Pitch Build & Monitoring

The design philosophy for AGPs is essentially two-stage, base design and surface system design. The base is designed to remain stable and level over the design life, typically 25 years, and provide adequate structural support, drainage and resistance to damage from frost penetration. The base also needs to be stable to support short-term loads such as construction plant. The underlying weaker soil requires protection, by the base materials, from the heavy (static or dynamic) construction repeated loads. If the soil is moisture susceptible (e.g. plastic clay, common in the UK) protection from excessive rain is also required during construction. Base construction utilizes standard construction plant and processes. The key engineering parameters that affect the base design are the ultimate strength (bearing capacity) and stiffness (resistance to deformation under load) of the soil and material layers, and their combined structure. Once the base is installed the loads transmitted to it by the players, or general maintenance plant, are considered relatively insignificant. There is a demand for innovation in bases to reduce the depth of quarried aggregates and asphalts, and improve water attenuation/storage capability to reduce local flood risk.

The surface system design is based on the play performance requirements of the sport(s). The ‘system’ comprises the shockpad, carpet and infills. In 3G systems infills are comprised of a lower layer of stabilizing sand and an upper layer of ‘performance’ infill commonly a (recycled) rubber particulate. The key play performance parameters for the user are shock absorbency (underfoot and impact comfort) and grip (traction), and ball sports include bounce and roll criteria. The system play performance response is a combination of shockpad type, density and thickness, carpet detail (fiber length, type, and weight/density) and infill types and depths [3]. Maintenance of the field, such as cleaning and brushing, is vital in prolonging good performance [4]. For this project the pitch build programme was from August through November 2014, the weather was unusually warm and dry, an advantage for the earthworks. The new pitch was constructed on the site of an existing natural turf pitch. The general testing position grid utilized is shown in Figure 1, showing the 19 designated points used for system approval testing [2], the lower layer monitoring used this system also for direct comparison albeit not all layers were tested at all positions.



Fig. 1. Testing grid layout, utilized for the monitoring. Pitch length 105 m, width 62.5 m.

2.1. Pitch Formation and Base

The base construction took 6 weeks. The formation soil was sampled and insitu strength measured (at 8 locations) by two common geotechnical methods, the portable hand vane (suitable for clays of strength up to 150 kPa) and the dynamic cone penetrometer (DCP), suitable for all soil types up to coarse aggregate size (i.e. < 63 mm). The DCP is correlated to soil strength (a bearing ratio, CBR %). Soakaway tests were performed at three locations to assess the in situ water infiltration rate (drainage potential) of the formation (clayey) soil. The contractor’s empirical design was a standard 300 mm depth of sub-base over the formation, which is common in the UK and suitable for formation soils of medium strength (>4% CBR). In the NE corner of the pitch a shallow lift of fill was required to maintain the formation levels, and utilized soils cut from the south-west corner.



Fig. 2. (a) sub-base compaction, note the geotextile separator (b) asphalt paving machine (c) shockpad paving machine (on blocks).

The sub-surface drainage system comprised lateral drainage channels across the pitch width at 10 m intervals, approximately 300 mm deep with 80 mm diameter perforated pipes installed at a cross fall of approximately 1 in 200, backfilled with 6-10 mm single size (pea) gravel. A central 160 mm carrier pipe was installed down the center of the pitch to collect water from the laterals and discharge to the pitch outfall on the north side, connecting into the local stormwater sewer system. The as built data is vital for detailed back-analysis of the system performance.

The formation soils were described on site as red brown stiff to very stiff red brown silty CLAY (weathered mudstone), which varied in the NE corner to more sandy CLAY. The silty clay soil had a natural water content (w/c) of between 22-29%, slightly above its plastic limit (PL) of 21-25%. The plasticity index (PI) of 27-33% (Liquid limit of 48-59%) classified it as CI/CH. The sandier clay soil had lower water contents of 13-17%, and lower PL of 15-16%, and PI of 17-18% (LL 33-34%), classified it as CL. The DCP and hand vane shear strength data showed the soils to be very variable, not uncommon in weathered clays. The inferred CBR ranged from 3-9% (above the design value) for the upper 300 mm, and hand vane 100 to >140 kPa, and due to the warm dry weather the upper layer of formation soil developed a stiff crust in exposed areas. The water infiltration rate from soakaways was negligible, suggesting very low permeability - as expected for plastic clay soils.

The aggregate sub-base had low fines to promote good drainage, and a geotextile used as a separator to avoid aggregate and soil mixing (see Figure 2a). The stone was laid using standard plant to a depth of approximately 250 mm, the final 50 mm was laid by a laser level controlled (asphalt) paving machine (Figure 2b) to providing a level surface for the asphalt. The sub-base compaction used a small vibrating drum roller, with repeat passes. The aggregate stability was assessed by three methods, the DCP (CBR %), the 4.5 kg Clegg Impact Hammer (routinely used to assess compacted state), and a portable plate testing technology familiar to the highways construction industry was also trialed. The 'Lightweight Deflectometer' (LWD) plate test utilizes a falling mass and rubber buffer to dynamically load a 300 mm diameter bearing plate to a controlled contact stress (100 kPa) and measures the surface deflection [5]. In the highways industry a minimum of 65 MPa is specified to ensure adequate compaction (of a well graded sub-base) and overall base stiffness. The minimum stiffness value suggested currently for a sport pitch sub-base is 40 MPa, reflecting the lower density and stability achieved with the lower fines. The formation had dried out in exposed areas at the time of placement of much of the sub-base expected to increase the measured stiffness. Samples of the sub-base were taken for further laboratory classification, compaction tests and water content. Pitch edging kerbs, fencing posts and floodlight columns were installed alongside the base construction works.

The DCP results from 6 positions on the compacted sub-base (when approximately 250 mm thick) gave low and variable results, range 4 to 11%, reflecting the low density achieved (a compacted well graded sub-base should achieve >30% CBR). The 4.5 kg Clegg gave impact values (CIV) of 9-18 gravities, which converts to a CBR range of 6-23%. A target value for CIV in small works is 28g. The LWD stiffness results ranged from 28-60 MPa across 8 test positions. The tests were not undertaken on the full thickness of sub-base and aggregate segregation was also considered to be the cause for reduced stiffness values. Further research is required to establish the LWD device and target values for routine use on sports bases. Aggregate sample water contents were in the range 0.4-2.3%, average 1%, expected for low fines aggregate (a well graded aggregate water content expected to be 3-5%). If aggregate internal strength is too low it can create issues of instability under heavy asphalt truck deliveries and asphalt paving, though this was not observed at this site. Analysis of the compacted density suggested approximately 25-30% void space, and hence high water infiltration and storage capacity. Approximately 526 000 liters of water could be stored, which represents a high intensity storm volume [6], and can be utilized to reduce flood risk.

The asphalt layer was constructed in one pass of 40 mm thick, and checked for planarity using a straight edge. LWD measurements were taken for further analysis of the structural capacity of the whole base. Asphalt increases in stiffness during curing, and field testing was commenced a minimum of 48 hours after compaction. The LWD stiffness data ranged from 81 to 105 MPa, average of 94 MPa. This demonstrates a big improvement from adding the thin bound layer to the sub-base aggregate. The LWD data were back-analyzed (using principles of linear elastic layered analysis) and estimated that the stiffness of the now confined sub-base layer had doubled. These stiffness analyses, novel to the sports industry, are important for benchmarking, setting appropriate site target values, analytical design, and assessing future innovative pitch base technologies.

2.2. Shockpad

The shockpad layer was designed to be 25 mm thick. It was constructed in situ (often termed 'wet-pour'), which is more common in the UK than prefabricated products, and took 5 days of the programme with additional 1-2 days curing. The recycled rubber granules (2-6 mm in size) and polyurethane binder were mixed in small batches and laid out ahead of the small paving machine, spread and compacted into 2.5m wide strips (see Figure 2c). The binder content, density achieved, and thickness of the shockpad affect its stress-strain properties [7]. Industry testing is usually required in the laboratory (e.g. for tensile strength, an indirect assessment of binder content and durability) as part of the sports bodies certification. More recently, the thickness and shock absorbency is measured both in the laboratory and field for compliance [2]. In this case study it was not part of the contract duties. The shockpad was tested at 19 positions (Figure 1), for thickness, shock absorbency (also termed force reduction (FR)), and 2.25 kg Clegg Impact Value. The contractor paved onto thin plywood boards to fabricate 1.5 m square samples for use in ongoing laboratory based research testing.

Table 1 presents the summary field data from the 19 positions, including 3 repeat tests at each position. The vertical deformation (VD) and Energy Restitution (ER) are further measures of hardness. In general the shockpad appeared to be consistent for both thickness and the play performance related parameters. The shockpad also plays a crucial role in providing shock absorbency for player head impact safety in rugby, although not part of this study the field passed this test (Section 3). The 1.5 m square samples recovered were analysed for density and Clegg impact for comparison to the field. The three samples gave

densities of 575-600 kg/m³, which represent the upper end of density (general range 500-600 kg/m³) from previous research of in situ shockpads [7]. The lab sample Clegg readings were in the range 95g to 117g, average 106g, very similar to the field data. The lab shockpad samples replicate the field product well, important for further research under controlled conditions.

Table 1. Field Shockpad Measurements

	Thickness (mm)	FR (%)	VD (mm)	ER (%)	Clegg (g)	Air Temp (°C)
Average Value	22.9	60	6.2	48	102	21
Maximum	25	65	8.4	50	117	24
Minimum	20	57	5.6	40	85	15

2.3. Carpet & Infill

The carpet installed comprised a 60 mm pile height product, described as ‘3rd generation football turf with sand and rubber crumb infill’. The carpet was laid in 4 m wide rolls, stretched and moved into place (see Figure 3a), and then seamed. Seams were fixed by gluing a 300 mm wide backing strip across the joint. The carpet took 10 days to install including cutting in some of the color line markings. The carpet was vigorously brushed whilst the stabilizing sand infill was applied using a large motorized hopper, to a target coverage rate of 15 kg/m² (see Figure 3b), taking 3 days to complete. A spreader machine was used to install the ‘performance’ infill (rubber granulate/crumb recycled from truck tires) to a target coverage rate of 15 kg/m², also taking 3 days to complete. It should be noted that the particle density of sand is more than two times that of the rubber hence the rubber infill depth (volume) is much greater than sand for the same mass. The field area is approximately 6560 m², and around 160 tonnes each of sand and rubber were applied.

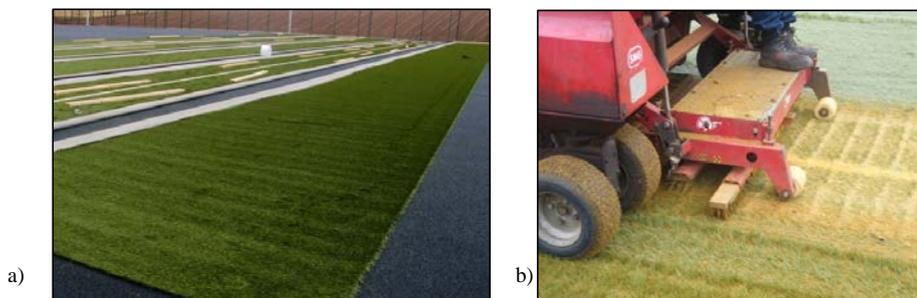


Fig. 3. (a) Artificial Turf carpet rolls laid out to relax prior to seaming; (b) Sand infill layer being applied by mechanized spreader and vibrating brush system.

One difficulty when reviewing past studies on different AGP's is finding any detail of the carpet specification and installation details regarding infill type, amount, depth etc. The carpet specification in this case was: Fibre yarn olive green, monofilament (single strands), average thickness 0.21 µm, width 1200 µm, yarn dtex 13000 (mass in grams per 10000 meters). Tufted carpet with 12 fibers per tuft, spacing of 160 tufts/m along each row and a row spacing of approx. 52/m (3/4" gauge). The carpet weight, including the backing (1000 g/m²) is 2690 g/m². The backing reinforces the carpet and increases the fiber ‘pull out’ resistance. Drainage holes punched through the carpet are 3 mm in diameter at 140 mm spacing.

Based on the field readings (using a hand held depth gauge) the total infill depth was around 40 mm. The sand infill was installed to a depth of approximately 11-13 mm, consistent for that coverage rate. The sand used (from the product data sheet) was ‘quartz’ with a particle size range of 0.25-0.71 mm, and sub-angular to rounded in shape. The rubber infill depth (by deduction from the total infill depths) was estimated as 27-29 mm. The recycled tire rubber crumb used (from the product data sheet) was predominantly styrene butadiene rubber (SBR). No size range was specified, but was estimated as 0.8 to 2.0 mm.

It is apparent that fine tuning of the play performance compressive parameters such as shock absorbency and ball bounce comes from the combined stress strain properties of the layers and their physical attributes including: porous shockpad [7] thickness and density; thickness and density of the sand; and thickness and density of the relatively compressible rubber infill. The carpet fibers provide stability to the rubber infill in particular, reducing its mobility and increasing stiffness and strength behavior. Large samples of the carpet and infills were retrieved from site to be utilized in laboratory based controlled studies.

3. Early Life ‘Play’ Performance

The installed field has been tested by an accredited test laboratory in accordance with the field's requirements for competitive level rugby union [2], and will require re-testing every two years to maintain approval. In the first year of its use (2015) the research team has carried out further programs of in situ testing. The results are presented in Table 2, showing the average results

and the range (\pm), for the 19 official test positions (Figure 1) except for ball tests done at 6 positions. Furthermore, the September testing was confined to one sub area of the pitch near the center circle. This pitch is also used for association football (and American Football) and as a result the ball roll behavior is of interest but not a requirement for rugby. In addition the free pile height (FPH) of the fibers was also measured in November 2014 and March 2015 at the 6 positions where ball roll was measured, with both data sets concurring at 19-23 mm. The FPH is useful as it has been shown to correlate strongly with ball roll and can be used to monitor the effectiveness of the brushing maintenance in keeping the fibers upright, previous work [8] suggests a FPH of 20 mm predicts a ball roll distance of approximately 6 m.

Table 2. AGP Play Performance Data – summary data from the first year of use. (note: mean \pm range)

Dates of Testing	Infill Depth (mm)	FR (%)	V.D. (mm)	ER (%)	Rot T (Nm)	VBR (m)	BR (m)	Clegg (g)	Air Temp (°C)
Nov 2014 (post-installation)	41 \pm 2	72 \pm 2	11.8 \pm 0.7	35 \pm 1	33 \pm 3.5	0.62 \pm 0.4	6.6 \pm 0.3	59 \pm 8	12 \pm 0.5
January 2015 (official tests)	42 \pm 1	67.5 \pm 1.5	10.6 \pm 0.4	34 \pm 2	35 \pm 2	0.74 \pm 0.3	--	--	12 \pm 2
March 2015	40 \pm 2	71 \pm 2	11 \pm 1	32 \pm 2	34.5 \pm 3	0.78 \pm 0.2	6.1 \pm 0.3	70 \pm 6	11 \pm 2
September 2015*	40 \pm 1	73 \pm 1	13 \pm 2	32 \pm 2	35 \pm 3	--	--	75 \pm 4	19 \pm 2
World Rugby Requirements	--	55-70	5.5-11	20-50	30-45	0.6-1.0	n/a	n/a	

Notes: FR = force reduction; VD = vertical deformation; ER = energy restitution; Rot T = rotational traction; VBR = vertical ball rebound; BR = ball roll distance.

The data in Table 2 supports the commonly held view that when first installed the pitch can take a while to 'bed in' (i.e. infill settlement/compaction causing some hardening) and it is usual to wait before the official testing is done as a consequence. The data in general show high shock absorbency and surface deformation (vertical deformation, VD), i.e. the surface is at the softer end of acceptability and close to the upper limit. Past research has shown that in general AGP's usually get harder with time so an initial 'softer' result is ideal. The ball rebound (a measure of 'resilience') is observed to have increased somewhat suggesting some densification of the (rubber) infill. The AGPs at Loughborough are heavily used (>60 hours per week) and the maintenance is largely carried out in-house, providing for useful synergy with the temporal research monitoring carried out. The year round maintenance schedule for this AGP is typical of the generic recommendations: weekly, litter pick (twice) and drag brushing (twice); monthly power brush and Hoover (combined process). The (static) drag brush is primarily aimed at levelling the infill evenly across the pitch, and reducing any compaction of the (upper) rubber infill by agitating it. The monthly power-brushing aims to clean the surface of detritus and help keep the fibers upright. The machine's contra-rotating brushes can be set to different depths. Experience thus far suggests that when very wet the brush depth is set to a shallower depth to avoid moving the infill too much. In year one only a small amount finer detritus material has been captured in the Hoover filter (any coarser infill picked up is returned by the filters) relative to experience of more detritus and fiber on the older AGP's. The surface has yet to require a top up of rubber, usually done sporadically and as required to maintain shock absorbency and the correct pile height above the infill (for ball roll). It has been anticipated that the surface should ideally last approximately 7 years, and to assist this target 'rejuvenation' of the surface is anticipated after 4 years comprising removal and replacement of the whole infill. Further monitoring will assist these important decisions and show the pattern of changes in play performance with use and wear.

4. Other 'performance' related monitoring

As part of the ongoing wider research aims the unique opportunity was taken to install a flowmeter in the drainage outfall chamber and thermocouples during construction. Space only permits a brief overview here. The drainage measurements form part of a wider study focussed on evaluating the attenuation and storage behaviour of sport pitches by monitoring discharge flows and local weather data, for both artificial (AGP) and natural turf pitches (NTP) [6]. The wider drainage study, aimed to inform practice, has shown that there is a lot of internal resistance to water flow within an AGP and NTP, such that peak rainfall intensities are greatly reduced (attenuated) at the discharge outlet. In most cases the % yield (volume discharged out / rainfall volume in) are 30-60% or lower. The data from this case study has shown very low yields and high attenuation to date.

Thermocouple transducers were installed at all layers in the pitch construction, in the clay formation layer, sub-base, asphalt, shockpad, carpet backing and the sand infill. It was not practicable to install the steel wire thermocouple into the rubber infill for safety reasons. The aims of this work were twofold: firstly and primarily to provide data for the evaluation and modelling of the heat exchange mechanisms through the pitch layers - it has been observed that on warmer sunny days the rubber infill can reach temperatures well in excess of the ambient air temperature and also that of natural turf surfaces [9, 10]. Secondly, the data help with the debate on frost protection related aspects of pitch base design from evaluation of the insulating effects of the upper pitch layers on the clay formation. Figure 4 provides an overview of the temperature monitoring over the period November 2014 to January 2016 at two depths, within the sand infill (a) and the formation soil (b). The sand data was so 'noisy' that the maximum and minimum daily temperatures are shown for visual clarity. A prolonged period of cold in Jan/Feb 2015 gave the lowest formation soil temperatures to date of 2°C. In July 2015 the temperatures in the sand infill peaked at 26.5°C and the rubber infill peaked at 58°C (measured by a hand held infra-red thermal camera) whereas the peak ambient air temperature was 24°C. The

formation soil temperatures (buried approximately 100 mm into the soil below the sub-base) did not fluctuate as much as the sand, as expected, but showed the same general trend over time. Interestingly the carpet (latex) backing and shockpad (also primarily rubber) displayed higher temperatures than the sand infill during this period. Early work on mathematically modelling the heat transfer has shown good agreement with the experimental data. The ongoing research aims to provide a design tool to predict the expected infill surface temperatures and air temperatures for a range of pitch designs and for a range of global climates. This unique work will then be integrated into studies on the potential for heat stress and player injury risk [10].

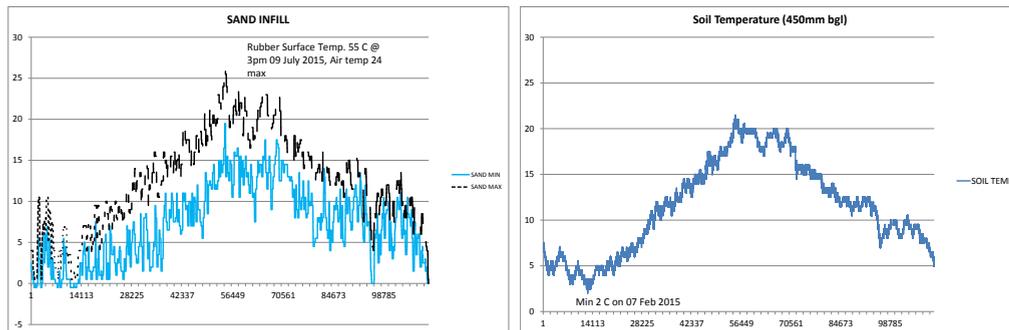


Fig. 4. (a) AGP sand infill temperature; and (b) formation soil temperature over a one year period

5. Discussion & Conclusions

The monitoring of the full build and early life of the artificial grass pitch on Loughborough campus has provided a unique insight into the processes and properties of the materials used and the sport system behavior and provided important properties and attributes for the ongoing research studies. The build data show the pitch to have been constructed to a good standard and to tolerance regarding the base, surface system and the first year of field play performance. The official testing by an accredited test laboratory corroborates well with field testing completed by the research team, with early indications of the pitch hardening slightly. The ongoing collection of field data by the research team, regarding the state of the surface system and play performance, usage rates and effects of maintenance processes, all provides new knowledge and insights into AGP performance, wear and degradation. Effective maintenance of AGPs is a topic of concern to the industry and this research adds unique quantitative data for future guidance. The opportunity to gather temperature data through the full depth of the construction is an exciting prospect for unique work on predicting behavior, as is the ongoing drainage monitoring to enhance sustainable design. There is an increasing requirement from international sport governing bodies for the artificial turf carpet manufacturer to be directly responsible for the whole pitch build and the management of the maintenance aftercare in relation to the contract warranty. This added responsibility has stimulated more interest in the whole-life behaviour and arguably will stimulate more innovation into sustainable design approaches and the need for more and better data collection regarding performance. This paper provides some useful techniques for monitoring build quality in particular, in addition to the in-service performance.

Within the advancing understanding of AGP behaviour it is important to recognize the increasing constraints of laboratory testing for recreating the appropriate simulated state of the sports surface systems as it exists in the field, in addition to the usual laboratory constraints of space and proprioception for subject studies. Whilst laboratory testing is still vital for investigating the effect of controlled changes in system components, it requires benchmarking to real world behaviour. The challenges of utilizing sports pitches for field research are many, though the intense study and ongoing data collection at this AGP will serve to enhance the validity and relevance of the current and future research studies by the research team.

Acknowledgements

The support of the AGP commercial team and University support staff, particularly head groundsman Mark Freeman.

References

- [1] Fleming PR, Artificial turf systems for sport surfaces: current knowledge and research needs, Proc. IMechE Vol. 225 Part P: June 2011 no. 2 43-63
- [2] World Rugby. Rugby Turf Performance Specification, 2015. Available at <http://www.irbplayerwelfare.com/>
- [3] Science and Engineering of Sport Surfaces, Editors S Dixon, P Fleming, I James, Matt Carre, published by Routledge ISBN: 978-0-415-50092-0
- [4] McLaren NJ, Fleming PR, Forrester SE. Artificial grass: A conceptual model for degradation in performance, Procedia Engineering 2012; 34:831-6
- [5] Frost M. W., Fleming P R, Gordon M, Edwards P J, Pavement Foundation Stiffness Testing – A New Regime, 2010, Proc. ICE Transport, 163; 119–125
- [6] Simpson, M J, Frost M W, Fleming P R, Briefing: Sustainable drainage for sports pitch developments, Volume 166 Issue 4, Dec 2013, pp. 211-215
- [7] Anderson L J, Elastomeric Shockpads for Outdoor Synthetic Sports Pitches, 2007, PhD Thesis, Loughborough University
- [8] McLaren NJ, Fleming PR, Forrester SE. Artificial Grass: A Longitudinal Study on Ball Roll and Free Pile Height, Procedia Engineering 2014; 72, 871–876.
- [9] Petrass, L. A., et al., Understanding how the components of a synthetic turf system contribute to increased surface temperature. Procedia Engineering, 2014; Volume 72, pp. 943 - 948.
- [10] Twomey, D. et al., 2014. Heat experienced on synthetic turf surfaces: An inevitable or preventable risk?. J of Sci and Med in Sport, Vol: 18, pp. 119 - 120.