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Lane, Benjamin David

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ADVANCED TECHNIQUES TO IMPROVE THE DESIGN OF TENNIS BALL CORES

A doctoral thesis submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

by

Benjamin David Lane

Wolfson School of Mechanical, Electrical and Manufacturing Engineering

Loughborough University

United Kingdom

2019

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Statement of Originality

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This thesis contains material from [x number] paper(s) published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as:

Lane, B., Sherratt, P., Hu, X., & Harland, A. 2016. Characterisation of ball impact conditions in professional tennis: Matches played on hard court. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology; 230(4), pp 236-245.

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In all instances the contributions of the co-authors are as follows:

- Prof Hu Xiao, Dr Paul Sherratt and Prof Andy Harland provided the initial project direction and edited the manuscript drafts.
- The raw data was supplied by Hawk-Eye Innovations.
- I processed the data and prepared the manuscripts.

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The contributions of the co-authors are as follows:

- Prof Hu Xiao, Dr Paul Sherratt and Prof Andy Harland provided the initial project direction and edited the manuscript drafts.
- I prepared the ball samples, prepared the laboratory and conducted all impact testing.
- I processed and analysed the data and prepared the manuscripts.

18/06/2019

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Date

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Benjamin Lane

Success is a journey not a destination.

The doing is usually more important than the outcome.

Arthur Ashe

Abstract

Over the past century tennis balls have seen little development, despite issues with durability and recyclability. Over the same period rackets have seen several development iterations through the use of wood, aluminium and carbon fibre reinforced composites frames. Players physical capabilities have dramatically improved and even line-calling has been automated. In professional tennis, balls are used for as little as nine games before being discarded, whilst recreational players demand a long-lasting product at minimal cost. Balls are comprised of a vulcanised rubber core, which is pressurised, and woven felt covering. Similarities in materials, combined with strict performance limits defined by the International Tennis Federation (ITF) and consumer pressures culminates in a product with low profit margins and little market differentiation. The work presented in this thesis focussed on the elastomeric material used to manufacture the core of tennis balls, presenting a scientific means of assessing alternative ball core materials that could benefit players and brands alike.

Ball tracking data collected during professional tournaments, spanning the major court surfaces used in professional tennis, was analysed and used to determine the impact frequency and conditions a ball is subjected to during play. The range of impact conditions determined were replicated in the laboratory and subjected to digital image correlation techniques (GOM Correlate Professional), which were applied to measure the surface strains and strain rates present during impact. The results of which enabled the transformation of typical ball impact conditions in professional tennis into mechanical testing conditions representative of what occurs during impact.

Current pressurised and pressureless ball core rubber were subjected to tensile testing, matching as closely as was possible, the strains and strain rates measured during impact. Dynamic mechanical analysis (DMA) was also utilised to characterise the viscoelastic properties of current ball core rubber. The characterisation of current materials provided a benchmark against which alternatives could be compared and enabled the implementation finite element (FE) simulations of ball cores during impact. FE modelling utilised advanced viscoplasticity material models (Bergström-Boyce model) enabling the viscoelastic and strain rate dependent behaviour of rubber to be incorporated, eradicating the need to artificially tune model coefficients, as seen in previous examples of tennis ball modelling.

Having quantified the conditions required for materials characterisation testing and developed a methodology for the simulation of pressurised ball core impacts, alternative

materials were identified and assessed. Thermoplastic elastomers (TPEs) were identified as materials with potential for replacing vulcanised rubber. TPEs offered potential improvements to pressure retention properties, recyclability as well as the opportunity to utilise thermoplastic manufacturing processes. When subject to the same materials characterisation testing and FE modelling as ball core materials, TPEs exhibited, in part, comparable properties to ball core rubber, with simulations estimating similar ball core performance for melt processible rubber TPE. The work presented in this thesis implies TPE materials are worthy of further investigation for use as tennis ball cores.

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Long live the tea break.

Publications Arising from this Research

Journal Articles

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Conference Proceedings

Lane, B., Sherratt, P., Hu, X., & Harland, A. 2014. Characterisation of ball impacts in professional tennis. *1st International Conference in Sports Science & Technology*, Singapore.

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Abbreviations

3D	Three-Dimensional
β	Beta Damping Coefficient
δ	Phase Angle
ε	Strain
$\dot{\varepsilon}$	Strain Rate
η	Viscosity Modulus
σ	Stress
χ^2	Chi-Squared Test Statistic
ω	Frequency
ANOVA	Analysis of Variance
BASF	Baden Aniline and Soda Factory SE
BB	Bergström-Boyce Model
CEL	Coupled Eulerian-Lagrangian
CF ₄	Tetrafluoromethane
COR	Coefficient of Restitution
CSV	Comma Separated Values
D	Diffusion Coefficient
d	Cohen's d effect size
DFM	Digital Fuzziness Metric
DIC	Digital Image Correlation
DMA	Dynamic Mechanical Analysis
DNF	Dual Network Fluoropolymer Model
DPG	Diphenyl Guanidine
E	Elastic Modulus
F	F-Distribution Test Statistic
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
fps	Frames per Second
G^*	Shear Complex Modulus

G'	Shear Storage Modulus
G''	Shear Loss Modulus
GC	Grass Court
GOM	Gesellschaft für Optische Messtechnik GmbH
GPF	General Purpose Furnace
h	Thickness
HBS	Cyclohexyl Benthiazyl Sulphenamide
HC	Hard Court
HSV	High-Speed Video
ISO	International Organisation for Standards
ITF	International Tennis Federation
J	Flux
MC	Men's Clay Court
MPR	Melt Processible Rubber
NR	Natural Rubber
P	Pressure
P	Permeability Coefficient
p	Partial Pressure
PBT	Polybutylene Terephthalate
phr	Per Hundred Rubber
PN	Parallel Network Model
rpm	Revolutions per Minute
S	Solubility Coefficient
SD	Standard Deviation
SF6	Sulphur Hexafluoride
SHPB	Split Hopkinson Pressure Bar
t	Time
Tan δ	Loss Tangent
TIFF	Tagged Image File Format
TN	Three Network Model
TPA	Thermoplastic Polyamide
TPC	Thermoplastic Copolyester

TPE	Thermoplastic Elastomer
TPO	Thermoplastic Polyolefin
TPS	Styrene Block Copolymer
TPU	Thermoplastic Polyurethane
TPV	Thermoplastic Vulcanizate
TPZ	Unclassified Thermoplastic Elastomer
V	Volume
WC	Women's Clay Court

Chapter 1. Introduction

1.1 Chapter Overview

The background to the thesis is presented, outlining the history of tennis balls and their developments since their invention. The current issues and potential benefits of improving ball design are proposed alongside the challenges in implementing a new design. The research aims and objectives are defined and a chapter-by-chapter overview of this thesis is stated.

1.2 Background

Since the development of lawn tennis from royal or real tennis in the 1870s, the ball has remained relatively unchanged. Real tennis used balls made from a stitched envelope of leather or cloth, which was stuffed with rags or horsehair. Tennis balls however, utilised vulcanised rubber, a discovery by Charles Goodyear in the 1850s. Initially, tennis balls were made entirely of rubber before becoming hollow and pressurised, with flannel cloth stitched around the outside of the ball to improve playing and wearing properties.

The first hollow cores were produced from a three-leaf clover shaped piece of rubber which was folded into a sphere and stitched, before being cured. The balls were chemically pressurised when heated. This method was replaced to improve uniformity and consistency of manufacture. Typically, two half shells are compression moulded and glued together to form the core. Flannel cloth was also replaced with melton cloth and the stitching with rubber seams. Balls were traditionally black or white in colour until 1972 when yellow balls were incorporated into the laws of the game, improving visibility to viewers on television (ITF 2014a).

Other than a change in colour, tennis balls have seen little change for over a century. In this time, rackets have changed radically from wooden to aluminium to carbon fibre frames, with incorporated electronics enabling performance metrics to be measured during play. Strings have developed from traditional natural gut fibres to synthetic polymer filaments and hybrids of the two. Players are fitter and stronger due to improvements in nutrition and strength and conditioning, and even line calling has seen innovation with the introduction of Hawk-Eye.

It is estimated in the region of 360 million tennis balls are produced each year (ITF 2017a), with tournaments such as The Championships at Wimbledon using as many as 54,000 each year (Warwick Business School 2017). In the United States alone an

estimated 124 million balls are shipped each year at a value of over \$86 million in 2015 (Tennis Industry Association 2015). Although vast numbers of tennis balls are sold each year, brand competition and consumer demands dictate that balls are a low profit margin item compared to rackets, footwear and apparel.

Despite large production volumes and a product which has changed very little, the ball and the industry are subject to several constraints. Consumers demand a product that is both cheap in price and long lasting, as it is a commodity item, necessary to play the game, that incurs frequent financial outlay. Consumer trends also vary geographically with consumers in the U.S. typically purchasing cheaper products and disposing after one use (Cross 1999). European consumers however, tend to purchase less frequently and try to make the balls last as long as possible. The main complaints with respect to durability come in the form of pressure loss, causing loss of 'bounce', and degradation of the felt, such that balls become bald with prolonged use. The short lifespan of tennis balls is further highlighted by the ball change policy of professional events; with balls replaced after as few as nine games.

The current manufacturing process requires a long and complex supply chain utilising in excess of ten raw materials from eleven different countries (Warwick Business School 2017). The manufacturing process is also labour intensive, a contributing factor in production typically occurring in lower labour cost countries. The number of raw materials, cost of distribution and labour-intensive manufacturing process, combined with the pressure of competition and consumers, implies tennis balls are a necessity for brands to be viewed as a specialty tennis brand, rather than purely a financially lucrative business opportunity.

Due to governing body test standards and the materials and manufacturing process being virtually the same across brands, there is little to no product differentiation. Investigating alternative materials and manufacturing processes could provide a marketable difference over competitor products.

The natural rubber used to produce tennis balls, is sustainable from a production viewpoint as it is naturally occurring and extracted from trees. Issues regarding sustainability arise once vulcanised, necessary to give the rubber the desired mechanical properties. Once vulcanised, the core of the ball cannot be recycled or reprocessed. Although some re-use initiatives have arisen, enabling balls to be re-pressurised, or ground up, and used in particulate form in surfaces, such as playground surfaces; the vast majority of the 360 million tennis balls produced each year end up in landfill (Sustainable City Network 2016, reBounces 2017).

Many of the global issues addressed surrounding current tennis balls are a direct consequence of the current core material of the ball. The rubber core determines the pressure retention capability of the ball, end of use recyclability and dictates the manufacturing process, since the felt is typically bought in from external suppliers. Furthermore, products released to market with the aim of improved durability (e.g. Wilson Double Core, Tretorn Micro X) only add to the current tally of raw materials and manufacturing processes. As a result, it is desirable for brands to find an alternative core material that can address the issues raised, enabling an improved product offering to consumers and differentiation from rival brands. This could be achieved by replacing the current vulcanised rubber core with an alternative material, providing any new ball can perform appropriately.

To drastically alter the current approach to manufacturing tennis balls, it would appear necessary to move away from vulcanised rubbers to reduce the number of raw materials and manufacturing processes. Since the current performance characteristics of balls are not deemed to be a significant issue (i.e. how they perform when within the defined International Tennis Federation (ITF) standards), a material which offers similar properties to that of vulcanised rubbers would be of interest, providing additional benefits concerning potential manufacture, durability or recyclability can be realised.

As a result, thermoplastic elastomers (TPEs) provoke interest as a group of materials that combine elastomeric material properties, required for a ball core material, with the processing capabilities thermoplastics. When heated above the melting temperature, TPEs melt and can be formed using traditional thermoplastic processing techniques (e.g. injection moulding, blow moulding). Thermoset or vulcanised rubbers do not experience melting and are more difficult to form as a result. Since the melting-solidification process is reversible, TPEs can be reformed making them recyclable, unlike vulcanised rubbers. The use of TPEs is growing and has, in many applications, replaced conventional vulcanised rubbers. TPEs have been utilised by automotive companies as interior and exterior trim components (e.g. bumpers, fascia, interior door trim), in medical applications (barrier films) and in sealants and adhesives. In addition, TPEs have been used in the sporting goods sector for shoes outsole materials and soccer ball bladders (Callister 2007).

Prior to introducing an alternative material, it is necessary to establish the working range of the material for the given application, such as the expected strains and strains rates, in addition to the properties of interest (e.g. tensile, compressive, shear, dynamic). A standardised test procedure can then be employed to characterise the materials of

interest and directly compare properties which are representative of the conditions experienced during use. To achieve this the working range of the current materials in use would need to be established and an appropriate testing procedure defined. In addition, current product lifespan is of interest, and when defined can be used to compare the longevity of current and new generation product offerings.

Materials characterisation provides a means of directly comparing the mechanical properties of different materials. Further investigation of a new materials applicability is required to determine how a given material performs in the context of the application. The most effective means of establishing ball performance is through physical testing. Obtaining many different materials and creating several prototypes for physical testing is not always feasible, due to the costs involved and quantities that may be required. Although, it would provide a direct performance comparison to current ball cores, it would be difficult to iteratively tune a given material or highlight properties that maybe inhibiting performance in a way that modelling techniques lend themselves to.

Finite element (FE) modelling techniques have previously been employed to simulate sports ball impact performance, including that of tennis balls and tennis ball cores (Cordingley 2002, Goodwill *et al.* 2005, Price 2005, Smith and Duris 2009, Pugh 2011, Sissler 2012). Modelling techniques are well suited to investigate multiple design iterations, such as geometry and material variations. In addition, modelling can be utilised to determine the properties of greatest importance by isolating given variables and visualising the predicted effect on performance. Once an initial base model has been established, altering the material to investigate the effect on performance is simple and relatively fast in comparison to creating prototypes and physical testing. The combination of material characterisation and FE modelling could provide confidence a given material will perform in a similar manner to current materials and warrants further investigation in the form of physical prototyping and impact testing and design iteration.

1.3 Research Aims and Objectives

It is evident that changes to tennis ball design could be beneficial to the consumer, tennis brands and the environment, providing an appropriate alternative can be found. A methodology to assess TPE ball cores is required, in attempt to address the aforementioned global issues with tennis balls. The implementation of an alternative material requires understanding of current performance, a means of assessing and comparing different materials applicability, and a means of assessing the alternative materials performance in the given context. Consequently, the research aims and objectives addressed in this thesis are:

Research Aims:

- Establish a materials characterisation test methodology, representative of the conditions a ball experiences during use, against which TPE materials can be directly compared to current ball core rubber.
- Characterise current ball core materials and potential TPE alternatives to assess similarity and identify potential alternative TPE materials for assessment as a tennis ball core.
- Develop a finite element model to predict and compare the behaviour of current ball cores to TPE alternatives during impact.

Research Objectives:

- Understand impact conditions tennis balls are subjected to during use.
- Determine how these impact conditions correspond to the material's mechanical properties.
- Measure material properties at impact representative strains and strain rates.
- Model the impact behaviour of current ball cores and assess the sensitivity to design changes (e.g. stiffness, internal pressure, damping).
- Identify possible alternative TPE materials for use in tennis ball cores which are potentially advantageous over current thermoset rubbers.
- Establish the mechanical behaviour of alternative TPE materials at impact representative strains and strain rates.
- Assess capability of alternative TPE materials performance as a ball core through finite element modelling.

1.4 Chapter-by-Chapter Overview

This research study has been conducted to develop improved tennis ball core design through advanced testing methods and FE simulations. Current ball core materials have a limited life-span whilst testing procedures to further understanding could be more representative of the conditions the ball is subjected to during use. Research has been conducted to better understand the demands placed on tennis balls and how this translates to more standardised mechanical testing parameters. Materials characterisation and FE modelling has been utilised in a bid to investigate potential alternative TPE materials. The culmination of research in these areas has identified possible alternative TPE materials and established a testing methodology representative of in-play demands.

The body of research has been conducted as a series of discrete studies linking to inform the development of the improved ball core design. A chapter-by-chapter summary has been provided outlining the subjects detailed in each section.

Chapter 2 Literature Review

A review of current literature has been conducted examining the properties of tennis balls and their constituent parts. Current materials, manufacturing methods and governing body regulations have also been reviewed alongside research focused on understanding impact mechanics. Previous attempts to improve tennis ball design are assessed and the potential benefits of TPEs highlighted. Furthermore, the means to assess material properties and applicability of FE modelling practices are established.

Chapter 3 Characterisation of Ball Impact Conditions in Professional Tennis

Ball tracking data from professional tennis tournaments, played across the major court surfaces, was assessed to establish the impact conditions a ball is subjected to during play. The number of impacts a ball is subjected to is determined and the impact speed and angles assessed, where possible, to inform future laboratory-based impact, degradation testing and the possible need for testing to be court surface specific.

Chapter 4 Determination of Ball Core Strain & Strain Rate During Impact

The strains and strain rates present during impact of the ball core against a rigid surface were investigated. GOM digital image correlation software was utilised to measure strains and strain rates across a range of impact conditions. A select number conditions were compared to previous FE modelling techniques to determine a range of strains and strain rates that occur during impact to inform material characterisation test conditions.

Chapter 5 Characterisation of Tennis Ball Core Rubber

The behaviour of rubber materials used in the production of current pressurised and pressureless tennis ball cores were characterised. The tensile properties from low to high strain rate were assessed using a combination of standard test equipment and a bespoke test rig. DMA was utilised to evaluate the viscoelastic material properties. The characterisation process provides standardised data against which alternative materials can be compared, as well as enabling the development of a test data driven FE model.

Chapter 6 Finite Element Modelling of Tennis Ball Cores

Advanced viscoplasticity material models were employed to produce FE simulations of pressurised and pressureless ball cores during impact. The techniques used enabled the incorporation of multi-strain rate tensile data and viscoelastic material properties, producing a model based purely on experimentally determined material data. Simulations were compared to GOM surface strain analysis results (Chapter 4) and the effect of changing material properties on ball core performance was assessed.

Chapter 7 Alternative TPE Materials for Tennis Ball Cores

Categories of TPE showing similar properties to natural rubber are identified, from which specific grades were sourced. The TPE samples were characterised following the process formed in Chapter 6, establishing the multi-strain rate and viscoelastic material properties. The properties of the TPEs were then directly compared to ball core materials.

Chapter 8 Finite Element Modelling of TPE Ball Cores

The FE modelling techniques developed in Chapter 6 were applied to a selection of the TPE materials previously identified in Chapter 7. Simulations provided a virtual estimation of the behaviour of the TPE ball cores during impact. The TPE ball core simulations are compared against current ball core performance measures.

Chapter 9 Discussion

The research aims and objectives detailed in Chapter 1 have been addressed with reference to the findings of entire body of research presented. The findings and limitations of the research are discussed.

Chapter 10 Conclusions & Recommendations for Further Work

The findings of the research are presented and potential areas for future work identified.

Chapter 2. Literature Review

2.1 Chapter Overview

A review of current literature has been conducted examining the properties of tennis balls and their constituent parts. Current materials, manufacturing methods and governing body regulations have also been reviewed alongside research focused on understanding impact mechanics. Previous attempts to improve tennis ball design are assessed and the potential benefits of TPEs highlighted. Furthermore, the means to assess material properties and applicability of FE modelling practices are established.

2.2 Tennis Ball Materials & Manufacture

2.2.1 Manufacturing Process

Tennis balls are almost exclusively manufactured in Asia, notably; Thailand, China, and the Philippines. The process itself is labour intensive due to the formulation, compounding, mastication and curing processes required in thermoset rubber production. The basic stages in the manufacturing process are as follows (ITF 2014b):

1. Raw rubber is initially masticated until the required viscosity is reached.
2. The formulation is compounded through the addition of fillers, plasticisers, vulcanising agents and accelerators as necessary.
3. The rubber is extruded into pellets.
4. The pellets are formed into half shells.
5. The edge of the half shell is buffed and a vulcanising rubber solution is applied to the edge.
6. Half shells are pressed together in a pressurised environment, forming an inflated core.
7. The core is buffed and a rubber solution is applied to the outside.
8. Two dumb-bell shaped cloth pieces, edge dipped in rubber solution, are placed around the core.
9. The balls are then moulded under heat and pressure to cure the rubber solution and complete vulcanisation of the core.
10. The balls are then steamed to raise the fibres of the cloth before logos are applied.

2.2.2 Cloth

Two types of cloth are typically used in the construction of tennis balls, Melton cloth and needle cloth. Melton cloth, sometimes referred to as Playne's cloth, is a woven felt made

from a mix of wool and nylon fibres. Traditionally produced in a satin weave, Melton cloth is mechanically felted and raised before being applied to the ball. Needle cloth is produced by mechanically entangling fibres, usually to a base cloth, by rapidly piercing a layer of fibres with barbed needles (Chen *et al.* 2001). Needle cloth is often cheaper than Melton cloth as it tends to contain a higher content of synthetic fibres. Satin weave balls are considered to have better performance and wear properties than needle cloth balls and are used in the majority of professional events (Steele 2006).

2.2.3 Properties of Cloth

Woven fabrics are constructed of two sets of interlaced yarn called the warp and weft, whereby the warp is at 90° to the weft and the interlacing pattern referred to as the weave. Woven fabrics, such as tennis ball cloth exhibit anisotropic mechanical properties whereby the properties differ significantly depending on the orientation of the test. The anisotropic properties of fabrics have been successfully incorporated into sports ball modelling. Price *et al.* (2006) modelled the effects of the anisotropic behaviour of a soccer ball carcass during impact whilst Sissler (2012) incorporated the anisotropic properties of tennis ball cloth into a finite element model of a ball impact. Incorporation of anisotropic cloth properties was able to capture asymmetric ball deformation and variation in ball rebound angle during normal and oblique impacts.

2.2.4 Rubber

Natural rubber is the name given to naturally occurring polyisoprene, which contains a single repeating unit of isoprene, with cis-1,4 geometric isomerism (Figure 2.1). Natural rubber is extracted from an emulsion produced by the rubber tree *Heavea Brasiliensis*. The emulsion, or natural latex, is also comprised of resin, proteins, mineral matter and water and is coagulated to separate out the crude natural rubber. Polyisoprene can also be produced synthetically, known as synthetic natural rubber, although it does not contain the non-rubber substances found in natural rubber. It is commonly referred to in terms of high and low cis grades indicating the degree of stereoregularity. High grades tend to contain 96-97% cis-1,4 polyisoprene as opposed to 92-93% in low grades (Nagdi 1993).

Figure 2.1 Chemical structure of cis and trans polyisoprene (Nagdi 1993).

Crude rubbers usually require further compounding to enhance particular properties required for the given application. Rubber used to make tennis balls typically contains fillers, plasticisers and accelerators. Fillers are used for either economic reasons or to reinforce the rubber, as opposed to plasticisers that soften the rubber or act as a processing aid. Accelerators increase the speed of vulcanisation and reduce cure time, typically by introducing sulphur into the formulation. Example rubber formulations for pressurised and pressureless ball cores are shown in Table 2.1, highlighting the dependence on many raw materials for manufacture.

Table 2.1 Example rubber formulations for a pressurised and pressureless ball core compound (in per hundred rubber, phr) (Blow and Hepburn 1982).

Pressurised Core		Non-Pressurised Core	
Natural rubber	100	Natural rubber	100
General Purpose Furnace (GPF) Black	30	High-styrene resin	30
Clay	32	Kaolin	20
Zinc Oxide	9	Stearic acid	2
Sulphur	3.5	Sulphur	2.5
Diphenyl Guanidine (DPG)	2	Accelerator	1
Cyclohexyl Benthiazyl Sulphenamide (HBS)	1		
Curing Conditions	2.5 min at 150°C	Curing Conditions	4 min at 150°C

2.2.5 Properties of Rubber

Elastic Properties

The mechanical properties of vulcanised elastomers are typically non-linear when assessing the load-extension curve of the material. Elastomers are also capable of undergoing large elastic deformations, several times the initial length of the sample, and return to its original shape on release of the applied load (Callister 2007). Although capable of recovering to its original shape, unloading of elastomers results in energy loss caused by internal friction, termed hysteresis. Hysteresis is characterised by the

loop formed in the load-extension curve during cyclic loading (Figure 2.2), whereby the area within the loop is equivalent to the energy lost, mostly in the form of heat (Nagdi 1993). Cyclic loading and unloading highlights another phenomenon, termed stress-softening or Mullins effect, whereby an elastomer experiences a reduction in stiffness during the first few loading cycles, demonstrating a strain history dependence. When subjected to repeated deformations the stress-strain curve of a rubber sample will tend towards a steady state with a constant stress-strain curve. The initial stress-strain curve is unique and varies with repeated deformation as a result of cyclic softening. The effect is more pronounced in vulcanized elastomers and is believed to be due to a breakdown in the structure which alters the stress-strain properties of the sample. This could involve a breakdown or slippage of links between filler and polymer, filler and filler, or within the polymer matrix. It has also been found that the rubber recovers to its original, pre-deformation state over time, with recovery occurring faster at higher temperature (Mullins 1969, 1986).

Viscoelastic Properties

Elastomeric materials also exhibit viscoelastic behaviour. Viscoelastic materials exhibit both elastic and viscous behaviour. The viscous behaviour results in a time-dependent, and therefore strain rate dependent, mechanical response to external forces that is between an elastic solid, obeying Hooke's law (stress is proportional to strain, 2.1), and a viscous liquid that obeys Newton's law (stress is proportional to strain rate, 2.2) (Gent 2001).

Hooke's law: $\sigma = E\epsilon$	Where stress (σ) is the product of strain (ϵ) and the elastic modulus (E)	(2.1)
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Newton's law: $\sigma = \eta\dot{\epsilon}$	Where stress (σ) is the product of strain rate ($\dot{\epsilon}$) and the viscosity modulus (η)	(2.2)
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When subjected to an applied stress the sluggish configurational changes to the complex entanglement of long chained molecules results in a lag between the applied stress and imparted strain. Viscoelastic behaviour is observed when holding an elastomer under either constant strain or constant stress conditions (Figure 2.2). When held at a constant stress elastomers experience creep, whereby strain increases with time to a maximum value as time tends towards infinity. When held at constant strain elastomers experience stress relaxation, highlighted by decay in the corresponding stress with increasing time. Hysteresis, creep and stress relaxation are examples of viscous effects as, unlike purely elastic materials, viscoelastic materials dissipate energy when subjected to an applied load.

Figure 2.2 (a) Hysteresis, (b) Creep in viscoelastic materials and (c) Stress relaxation in viscoelastic materials.

Dynamic properties

The dynamic properties of elastomers are those linked to the short-term behaviour of the material, as opposed to creep and stress relaxation which interrogate the long-term viscoelastic properties. These short-term properties are typically determined using a forced vibration machine, such as dynamic mechanical analysis (DMA), that subject the sample to an oscillatory strain at a given maximum strain amplitude (ε_0) and angular frequency (ω). As elastomers are viscoelastic, the imparted strain is out of phase with the stress such that the deformation lags behind the imparted force by the phase angle (δ) (Figure 2.3), with stress and strain calculated using equations (2.3) and (2.4). A purely elastic material would exhibit in-phase stress and strain whilst the strain would lag stress by 90° for a purely viscous material. The complex modulus (or dynamic modulus, 2.5) is considered as having two vector components, one in phase with displacement (storage modulus, 2.6) and one 90° out of phase (loss modulus, 2.7). The storage modulus represents the elastic portion and is a measure of the stored energy, whilst the loss modulus represents the viscous portion and the energy dissipated as heat. The damping properties of the material are measured using the loss tangent ($\tan \delta$) which is the ratio between the storage modulus and loss modulus (2.8) (Brown 1996). The dynamic properties of elastomers are dependent on both frequency and temperature, such that the temperature or frequency-dependent properties of a linear viscoelastic material can be determined by testing.

$$\varepsilon = \varepsilon_0 \sin(\omega t) \quad (2.3)$$

$$\sigma = \sigma_0 \sin(\omega t + \delta) \quad (2.4)$$

$$G^* = G' + iG'' \quad (2.5)$$

$$G' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \quad (2.6)$$

$$G'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta \quad (2.7)$$

$$\tan \delta = \frac{G''}{G'} \quad (2.8)$$

Figure 2.3 Phase lag present during dynamic testing.

Permeability to Gas

To design a material for a specific application, such as a gas barrier, it is important to understand how the molecular structure of the material affects the application in question. With respect to the permeation of gas through polymeric materials the rate of gas transport can vary by many orders of magnitude. It is generally accepted that all polymers are permeable, to some extent, to all gases and that all molecules diffuse in molecular form, unless the gas is monatomic (Stern and Frisch 1981).

Much research has been conducted concerning the permeation of gas through polymers, particularly in the subject area of membrane science (Barrie *et al.* 1962, Cussler *et al.* 1988, Freeman 1999, Johnson and Thomas 1999); from which it is determined that the most common and widely accepted model for explaining gas transport phenomena through dense polymeric material is the solution-diffusion model (Wijmans and Baker 1995). The solution-diffusion model expresses gas transport in terms of a flux driven by a concentration gradient across the membrane. Alternative models include viscous flow, Knudson flow and molecular sieving for explaining mass transport through porous materials (Figure 2.4).

Transport of small molecules through a polymer membrane occurs due to random molecular motion (Crank 1975). The transport process ultimately involves the sorption

of the gas into the material, diffusion of the gas through the material and evaporation of the gas on reaching the downstream side of the material. A concentration gradient between the upstream and downstream sides of the material results in a chemical potential that drives the permeation process (George and Thomas 2001). Permeation is the result of a natural longing for equilibrium between upstream and downstream.

Figure 2.4 Mechanisms of the flow of gas molecules: (A) viscous flow, (B) Knudson flow, (C) molecular sieving, (D) solution-diffusion. Adapted from (Fried 2003).

Knudson flow is a mass transport method applicable to porous media. The flow of gas molecules depends on the size of the pores in relation to the mean free path of the gas molecules, whereby mean free path is the average distance travelled by gas molecules between collisions. The ratio of mean free path and pore size is known as the Knudsen number. Knudsen flow occurs at large Knudsen numbers, whereby diffusing molecules collide more frequently with the walls of the pores than they do with themselves (Uhlhorn *et al.* 1989, Fried 2003). Gas molecules are temporarily absorbed onto the surface of the pore wall on collision, and rebound off in a random direction. Consequently each molecules moves independently of each other and separation can be achieved as different gasses move at different velocities (Pandey and Chauhan 2001).

Viscous flow applies when the ratio between mean free path and pore size is small, inferring small Knudsen number. In viscous flow the molecules collide more frequently with each other than they do with the walls of the pores, consequently flow is proportional to the viscosity of the gas (Fried 2003).

Molecular sieving acts as the name suggests and tends to have higher productivity and selectivity than solution diffusion mechanics (Way and Roberts 1992). Molecules with a diameter less than the diameter of the pores in the material are able to pass through whilst larger molecules cannot. Molecular sieving is typically used to separate molecules

when the smallest molecule has a much faster rate of diffusion (Koros and Fleming 1993).

The solution-diffusion model applies to mass transport through non-porous materials. The model combines the theory of both solubility and diffusivity to explain permeation. Solubility is the capacity of a polymer to uptake penetrant gas, a process that occurs until equilibrium is reached. The process of diffusion is described by Fick's first law, whereby the flux in the direction of the flow is proportional to the concentration gradient. Fick's laws provide explanations for ideal cases of diffusion whereby the membrane is isotropic and the diffusion coefficient is independent of distance, time and concentration. Not only can strong polymer-penetrant interactions affect the rate of diffusion but generally experiments are conducted across a small range in concentration. Resulting diffusion coefficients may therefore be negligible. As the flow of diffusing molecules is constant and the diffusion coefficient is independent of concentration in steady state diffusion, the flux (J) is often expressed in terms of the diffusion and solubility coefficients (D, S), the partial pressure on either side of the membrane (p_1, p_2) and the membrane thickness (h) (2.9). Equation (2.10) gives the commonly known permeation equation. As permeability is the product of solubility and diffusion, the coefficients can be substituted with the permeability coefficient (2.11).

$$J = \frac{DS(p_1 - p_2)}{h} \quad (2.9)$$

$$P = DS \quad (2.10)$$

$$J = \frac{P(p_1 - p_2)}{h} \quad (2.11)$$

Factors Affecting Permeability

As permeability is a combination of both solubility and diffusivity, factors that affect either one or both of these phenomena will indirectly affect permeability. With regards to tennis balls, both the gas used to pressurise the ball and the rubber used to produce the core can be altered to improve the permeation properties and consequently prolong the life of the ball. As equation (2.11) shows, increasing the pressure differential increases the permeation of gas, whilst increasing the thickness of the rubber has the opposite effect. Solubility is dependent on the compatibility of the specific polymer-gas pair and can be influenced by the presence of polar groups and the incorporation of plasticisers. Polar gases dissolve more readily with the increasing presence of polar groups in the rubber,

whilst non-polar gases dissolve more readily in non-polar rubbers (van Amerongen 1964).

Gas-Related Properties

The major properties of the gas that influence diffusion are the size and shape of the molecules, albeit the effects are more marked in glassy polymers (Stannett 1968, George and Thomas 2001). Diffusivity decreases with increasing molecular size. Furthermore, as molecule size increases, the difference in the rate of diffusion of the gas in different rubbers increases. The rate of diffusion however is not inversely proportional to the square root of molecular weight, which is the case for diffusion through open pores; this is primarily due to the shape of the molecules. The shape of the molecule has a large impact on the diffusivity of the gas, for example, elongated molecules have higher diffusion coefficients than spherical molecules of the same molecular volume.

Rubber-Related Properties

Smooth, easy diffusion of small molecules through rubber is a common occurrence predominantly due to unsaturation, segmental mobility and free volume. The addition of plasticisers has a similar effect, increasing the segmental mobility of the polymer, resulting in increased permeation (George and Thomas 2001).

The diffusion coefficients of small molecules in polymers have been shown to be strongly dependent on the chain-packing density and consequently the free volume within the polymer. The distribution and dynamics of free volume within the polymer are dependent however on chain flexibility. As a result, for a given free volume, the diffusion coefficient and apparent energy of activation of diffusion are dependent on polymer chain flexibility (Takeuchi and Okazaki 1990). The addition of side groups, such as methyl groups, cause steric hindrance which increases the rigidity of the polymer and reduces the free volume for diffusing molecules to occupy. Flexible linkages, such as oxygen, in the polymer backbone can have the opposite effect as segmental mobility is increased (Ghosal and Freeman 1994). It appears that the presence of methyl groups and other bulkier groups has a greater impact on diffusivity if present in the form of side chains compared to if they are incorporated into the main polymer backbone. Bulky hydrocarbon groups can have the opposite effect however, as chain segments can be pushed further apart, increasing free volume and reducing rigidity and the influence of intermolecular forces, resulting in increased permeability (Pandey and Chauhan 2001).

The types of crosslink present also influence the permeability of a given polymer with a given crosslink density. This is a result of the chosen curing process utilised to vulcanize the material (Unnikrishnan *et al.* 1997, George and Thomas 2001). Peroxide vulcanization forms direct covalent bonds between the polymer backbones of adjacent polymer molecules, minimising free volume and segmental mobility, in turn minimising permeability compared to alternative vulcanization methods which results in monosulphidic, disulphidic, polysulphidic linkages (or a mixture of) between the polymer molecules.

Fillers are compounding ingredients added to crude rubber to alter properties. Typical fillers include carbon black, mineral fillers and lamellar fillers and are usually added in powdered form. The effect of fillers on the diffusion coefficient of a given polymer is dependent on the nature of the filler, the degree of adhesion with the polymer matrix and their compatibility with the polymer matrix. If the filler used is both inert and compatible, the filler will occupy free volume within the polymer matrix and increase the degree of tortuosity of the material. The degree of tortuosity is reliant on both the shape and orientation of the filler particles. If the filler is incompatible with the polymer, permeability tends to increase due to the formation of voids within the polymer matrix which leads to an increase in free volume (George and Thomas 2001).

Lamellar fillers have the potential to reduce diffusivity by 60-70%, and are appreciably more effective than non-reinforcing fillers which tend to reduce diffusivity by 10-15% when 0.7-0.18 volume fraction is added to the formulation (van Amerongen 1955, 1964). The effectiveness of lamellar fillers is predominantly due to their high geometric impedance factor. Penetrants diffuse through homogeneous structures in a straight line across the width of the material. The filler particles act as a barrier to advancing permeants, forcing them to take a less direct route through the structure, resulting in an increase in the time it takes for molecules to diffuse through the material. Consequently, the particles create a more tortuous path for the penetrants, thus reducing diffusivity (Figure 2.5) (Karimi 2011). Aspect ratio of the filler particles and the angle of the particles to the diffusion path have the largest influence on the effectiveness of the filler at reducing permeability. High aspect ratio fillers aligned perpendicular to the direction of gas transport offer the largest reduction in permeability (Goldberg *et al.* 2002a).

Figure 2.5 Effect of fillers on path of diffusion, adapted from (Karimi 2011).

More recently, literature has focussed on the benefits of using polymer nanocomposites for barrier applications. Filler particles in the nanometre-range dispersed within the polymer matrix have been shown to reduce permeability to gases, particularly when the particles have a high aspect ratio and are aligned perpendicular to the direction of diffusion. Much attention has been given to clay-based nanofillers, such as vermiculite, as they are cost-effective and can be effectively dispersed and aligned to maximise the tortuosity of the barrier (Zeng *et al.* 2005, Takahashi *et al.* 2006).

2.3 High Strain Rate Testing of Rubber

The mechanical properties of elastomers are highly rate-dependent due to their high viscoelasticity. When assessing elastomeric materials for a given application the strains and strain rates demanded by the application should be considered to truly understand the mechanical properties for the range of interest. Typically, the mechanical properties of elastomers are characterised using uniaxial screw-based load frames, capable of testing in tension and compression, in addition to other modes of deformation. This type of machine is typically limited by a crosshead speed in the region of $50\text{--}1,000\text{ mm}\cdot\text{min}^{-1}$, resulting in a maximum achievable strain rate in the region of 0.5 s^{-1} when testing an ISO 37 type 1 test specimen in tension. Electromagnetic dynamic load frames (e.g. Instron ElectroPuls E3000) have improved capability with respect to strain rate, with oscillations with an amplitude of 16 mm and frequency in the region of 5 Hz possible ($\approx 6\text{ s}^{-1}$ strain rate). Despite being accepted as standard practice for low strain rate testing neither are capable of testing at the high strains and high strain rates that occur during ball impacts, where strain rates in the region of 300 s^{-1} have been estimated through simulations (Cordingley 2002).

Due to the strain rate limitations of commercially available load frames, alternative means of capturing large strain, high strain rate behaviour of elastomers have been deduced. High strain rate in tension is considered as rates in excess of 10 s^{-1} (Hoo Fatt and Bekar 2004). It is a topic which has received attention since the early 1950s, with investigations into the tensile strength and breaking extension of different rubbers at strain rates as high as 1000 s^{-1} (Villars 1950, Kainradl and Handler 1962). Early high

speed tensile testing was limited by non-uniform rates of extension, and complete stress-strain curves were difficult to obtain because computerised data acquisition was not developed at the time (Hoo Fatt and Bekar 2004).

Servo-hydraulic test machines, driven by pressurised fluid (e.g. Instron VHS 8800 High Rate System), are capable of large displacements at speeds in the region of $25 \text{ m}\cdot\text{s}^{-1}$ (Roland 2006). Despite being commercially available they are vastly expensive and limited to a handful of institutions. Generally, they are setup to test stiff materials such as metals and concrete, which requires the capture of substantially higher loads than what would be experienced testing soft materials such as elastomers.

Intermediate and high strain rate testing of elastomers in compression can be achieved using commercially available drop towers and, commonly, Split Hopkinson Pressure Bar testing (SHPB). Drop towers utilise a guided drop mass to compress the sample material, with the combination of drop height and mass used to control the observed strain rate. Strain rates up to around 200 s^{-1} have been measured in soft silicone-based elastomers (Payne 2015).

The SHPB approach is used to test materials at very high strain rates (upwards of 1000 s^{-1} (Song and Chen 2003)) and can be applied in different deformation loads (tension, compression and torsion), although compression is the most common. In compression, a cylindrical test specimen is sandwiched between an incident bar and a transmission bar. A third striker bar is fired into the incident bar and the reflected and transmitted pulses are measured from attached strain gauges, from which the stress strain properties can be deduced (Figure 2.6)(Bergström 2015). SHPB is typically used to obtain data at strain rates in the thousands rather than the hundreds (s^{-1}) as it can be difficult achieving uniform stress through the sample, particularly when testing soft materials. Further challenges include barrelling of the sample, resulting in unwanted shear stress present in the sample, and achieving constant strain rate. Issues which are also common when testing with guided drop towers.

Figure 2.6 Schematic of a Split Hopkinson Pressure Bar test in compression.

Although usually equipped to test materials compressive behaviour, a tensile version of the SHPB has been used to test silicone rubber at strain rates between 750 s^{-1} and 1200 s^{-1} (Shim *et al.* 2004). Minimum reported strain rates for SHPB of 650 s^{-1} in compression

and 800 s^{-1} in tension, exceeding what is expected in tennis ball impacts (Mott *et al.* 2007).

High strain rate in tension not common because elastomers are not generally used in tension where they are flexible and weak (Hoo Fatt and Bekar 2004). Consequently, researchers have sought bespoke solutions to assess the tensile properties of rubbers at strain rates in the region of $10 - 1000\text{ s}^{-1}$. The approaches adopted have included utilising a drop mass, or pendulum mechanism, to accelerate and extend the test sample either directly, or through a mechanism such as a hinge or pulley (Hoo Fatt and Bekar 2004, Mott *et al.* 2007, Roland *et al.* 2007). Bespoke rigs have been shown to achieve rates up to and surpassing that simulated in tennis ball impacts (480 s^{-1} (Hoo Fatt and Bekar 2004); 570 s^{-1} (Roland *et al.* 2007); 284 s^{-1} (Mott *et al.* 2007)). In addition, the rigs in question have been capable of testing at intermediate strain rates from the maximum achievable by commercial electrodynamic load frames to the high rates stated, ensuring the range of interest for ball impacts can be covered. The challenge lies in developing a bespoke rig capable of achieving the desired results in house, in addition to the difficulties obtaining a relatively constant strain rate.

2.4 Thermoplastic Elastomers (TPEs)

TPEs combine the mechanical properties of thermoset rubbers with the thermally reversible behaviour of thermoplastics. The majority of TPEs are biphasic materials, containing a semi-crystalline (hard) phase, with an elastomeric (soft) phase (Kear 2003, Drobny 2007, Shanks and Kong 2012). The phases can be bonded chemically, producing long molecular chains of alternating hard and soft phases. Otherwise the two phases can be finely dispersed within the material. The hard phase provides the TPEs strength, acting much like the chemical crosslinks present in thermoset rubbers, without which the soft phase would be free to flow under an applied stress. The soft elastomer phase gives the TPE flexibility and elasticity. The service temperature range of a TPE is governed by the thermal properties of the individual phases, such that the useable range of the material falls between the glass transition temperature of the soft phase and the glass transition or melting temperature of the hard phase.

Physical thermo-reversible networks are present in most TPEs and are not permanent, breaking down at elevated temperature. It is this property of TPEs that is advantageous over vulcanised rubbers, enabling the use of plastic processing methods such as injection moulding, blow moulding and rotational moulding (Quirk and Zhuo 2000, Kear 2003, Shanks and Kong 2012). Plastic processing methods are simpler, more efficient and have shorter fabrication times than thermoset rubbers, due to the elimination of

mastication and curing. Certain processing methods (e.g. injection moulding) also offer closer part tolerances than can be achieved when forming thermoset rubbers. The need for compounding is also minimal or eliminated as TPEs are usually supplied formulated. Furthermore, reject parts and scrap material can be reground and reused, reducing waste. Despite a potential reduction in processing costs, the overall part cost for TPE materials can be significantly higher than a thermoset equivalent due to the unit cost of the raw material. Given the level of competition and consumer pressures present in the tennis ball market, the cost of any new product will be of great importance.

In contrast to vulcanised rubbers, TPEs typically require drying prior to processing to reduce the moisture content from the granulated material and reduce the risk of defects when processed. There is a limited availability of low hardness TPEs in the market, which could limit the number of TPEs with properties comparable to that of ball core rubber. Furthermore, in being thermoplastic, the upper service temperature can be relatively low (as low as $\approx 100^{\circ}\text{C}$, more commonly $\approx 150^{\circ}\text{C}$) (Drobny 2007). Heat generated in the core material during impact could be an issue for a TPE ball core, particularly as tennis is often played in hot weather.

TPEs have found use in many applications previously occupied by thermoset rubbers. The automotive industry accounts for 33% of TPE consumption for seals, hoses, boots and trim components (Drobny 2007). TPEs have also seen significant use in footwear (10.2%), as outsole materials, as well as in sporting and leisure goods (4.3%) as ball bladders and grips. This highlights that TPEs have a wide range of properties and uses, which combined with potential benefits over thermoset rubber, make TPEs worthy of investigation for use in tennis ball cores.

2.5 Tennis Ball Regulations & Test Standards

Tennis balls are regulated by the international governing body, the ITF, who have defined the standards in place to ensure balls are fit for purpose. The ball must have a uniform outer surface consisting of a fabric cover, whilst any seams must be stitchless. The colour of the fabric must be either white or yellow and the core may be pressurised or pressureless (ITF 2014c). Different ball types are defined for use in different conditions, such as varying court pace or high altitude, in addition to children specific types. The exact specifications of each ball type are published annually by the ITF (ITF 2017b).

To preserve the nature of the game and ensure that the balls used in professional events are fit for purpose, tennis balls must pass ITF ball approval. ITF approval consists of

several tests to determine if the properties of the ball are suitable for playing the game. The properties of the balls are scrutinised in terms of their mass, size, colour, rebound height, and deformation. The durability of balls is also examined, with limits set as to how much the properties of the ball are allowed to change in order to comply. The specifications of the test methods and allowable limits are defined by the ITF (ITF 2017b), who also publish a list of approved balls and accompanying type annually (ITF 2016).

The purpose of the ball standards and approval process is to create consistency and uniformity in ball performance. It is required for a ball to be used in an ITF regulated event and is sometimes a prerequisite of retailers when purchasing from brands. As such, any new ball would be required to conform to ITF standards and pass the ball approval process to prove successful.

2.6 Ball Impact Mechanics

Stiff thin-walled spheres, such as tennis balls, derive their global response from a combination of the bending of the material, geometry, and the gas pressure increase due to volumetric changes (Hubbard and Stronge 2001). Ashcroft and Stronge (2003) indicated that internal pressure adds stiffness to the ball, with the internal pressure contributing 59% of the overall stiffness of a pressurised tennis ball and 26% for a pressureless ball. Cross (1999) estimated for a rubber core with an internal pressure of 80 kPa, wall stiffness is increased by approximately 30% due to internal pressure.

The changing internal pressure is critical in understanding the rebound characteristics, but the pressure itself can be viewed as dependent on the global ball stiffness. When a ball is pressurised, the material is under balanced biaxial tension (Abeyaratne and Horgan 1984). As it becomes deformed the areas of high stress appear laterally in more of a hoop configuration, following the circular equator parallel to the impact plane. The dominant deformation modes experienced during normal impacts are lateral hoop strains and longitudinal bending (Cordingley *et al.* 2004). The resulting tension in the outer surface of the ball explains why balls are significantly stiffer than their associated cores, as Melton cloth is relatively stiff in this mode.

When impacts are carried out in the laboratory or simulated virtually, several standard measurements are taken to characterise the balls behaviour. Coefficient of restitution (COR), contact time, contact force, contact area, and deformation are used to describe ball performance (Cordingley 2002, Goodwill *et al.* 2005, Price 2005, Allen 2009, Sissler 2012, Hanson 2014).

2.6.1 Coefficient of Restitution (COR)

COR is the 'big picture' of energy in an impact, using one number to describe the complex interaction between objects as well as their individual behaviours. The COR of a ball during impact is the ratio of outbound velocity to inbound velocity or the square root of the ratio of rebound height to initial drop height. COR provides a measure of the energy lost during impact and forms part of the ball approval process in the form of the drop test, whereby a ball dropped from a height of 254 cm onto a rigid surface must have a rebound height that corresponds to a COR between 0.73 and 0.76 to conform (type 2 ball) (ITF 2017b).

It is suggested there are three modes of energy dissipation; plastic deformation, vibration and dissipation through viscoelastic properties of the bead and target (Falcon *et al.* 1998). A consequence of the time-dependent nature of the materials, COR has been found to decrease with increasing impact velocity (Caffi and Casolo 1995). Research has found COR to decrease from 0.75 at $7 \text{ m}\cdot\text{s}^{-1}$ to 0.4 at $45 \text{ m}\cdot\text{s}^{-1}$ (Miller 2006). Differences have also been found between pressurised and pressureless balls, particularly at velocities below $30 \text{ m}\cdot\text{s}^{-1}$, with COR for pressurised and pressureless balls tending to converge for impacts above $30 \text{ m}\cdot\text{s}^{-1}$ (Miller and Messner 2003). These results highlight that as impact velocity increases, energy loss also increases. Internal air pressure has the effect of reducing energy loss as naturally aged (longer than 6 months) and punctured balls show reduced COR on impact (Haake *et al.* 2003, Steele 2006).

2.6.2 Contact Time

Contact time for tennis ball and ball core impacts have been investigated and compared to finite element models. Both balls and cores have a contact time between 2 and 5 ms at impact speeds between $5 \text{ m}\cdot\text{s}^{-1}$ and $65 \text{ m}\cdot\text{s}^{-1}$ (Cordingley 2002, Allen 2009, Sissler 2012). Increasing impact velocity reduces contact time, although naturally aged balls with reduced internal pressure, and punctured balls show increased contact time (Steele 2006). Punctured ball cores were found to have higher contact times (4-6 ms) compared to pressurised equivalent for impacts between $5\text{-}30 \text{ m}\cdot\text{s}^{-1}$ (Allen 2009). Complete balls have significantly lower contact time than cores (8% lower on average) highlighting how the ball has increased stiffness over the associated core (Cordingley 2002).

2.6.3 Contact Area

The area of the ball in contact with the impact surface has seen some attention (Cross 1999, Cordingley 2002). It is believed the point of initial contact on the ball is not in

contact with the surface around maximum deformation. It is suggested that bending within the wall of the ball causes the point of initial contact to rise off the surface creating a gap. Inconclusive attempts to measure this phenomenon were made by Cordingley using laser doppler vibrometry.

2.6.4 Contact Force

Unlike contact time, contact force increases with ball impact velocity (Cross 1999). Peak contact force occurs approximately 0.2 ms into impact and is believed to occur as the walls of the ball buckle. Cross (1999) also utilised the impact force and deformation measurements to show the dynamic stiffness of a ball during impact is an order of magnitude greater than its quasi-static stiffness.

2.6.5 Deformation

Used by the ITF as a measure of stiffness by subjecting the ball to a defined load and assessing the deformation. This is a quasi-static test and isn't particularly relevant to high speed impact scenarios. Deformation is related to the force acting upon the ball such that deformation increases with impact speed. Deformation of balls, particularly in the case of normal impacts, is assessed in terms of the deformation parallel to the surface (tangential deformation) and normal to surface (normal deformation) and has been used along with contact time and COR as a means of validating FE simulations.

Influences on deformation caused by the presence of the seam and its orientation were not found to affect the performance of tennis ball cores during normal impacts when drop tested from 254 cm and during high velocity impacts against a rigid plate ($30 \text{ m}\cdot\text{s}^{-1}$). Consequently, the presence of the seam was omitted from finite element simulations (Sissler 2012).

2.6.6 Oblique Impacts

Investigations into oblique ball impacts have mostly focussed on spin generation and assessing court pace (Cottey 2002, Brody 2003, Cross 2003, Goodwill and Haake 2004, Haake *et al.* 2005, Stronge and Ashcroft 2007, Allen *et al.* 2011). As with normal impacts, analytical modelling approaches to predict deformation and spin have been superseded with FE simulations. Impacts that occur during a match usually have a much larger horizontal component of velocity than normal component. On impact with the surface the horizontal velocity decreases swiftly by an amount dependent on the angle of incidence, the coefficient of sliding friction between the ball and the surface, and pre-impact ball spin rate (Cross 2003).

Cross (2003) found the COR can be larger for an oblique impact compared to a normal impact. Cordingley (2002) separated the tangential and normal components of COR and found the normal component to be independent of inbound angle and tangential velocity, suggesting that energy loss as a consequence of material properties and impact vibrations was entirely a result of the normal component of impact. Furthermore, Cordingley found the tangential component of COR to be proportional to the energy loss due to friction, and as a result of all other energy losses being attributed to the normal component of impact, implied tangential losses were purely a consequence of friction. This was queried however as the frictional force is dependent on normal load, contact area and sliding velocity. The dependence on normal load indicates the normal and tangential components are not completely separate.

Oblique impact scenarios are complicated further with the inclusion of spin. The translational and rotational velocity of the ball, as well as the impact angle have all been shown to affect the observed impact condition (Allen *et al.* 2011). For impacts with zero pre-impact spin, increasing the tangential velocity linearly increases the outbound spin. Additionally, impacts at different angles with the same tangential velocity result in the same spin rate, indicating the normal component of impact velocity has no effect on spin generation (Sissler 2012). Allen *et al.* (2011) investigated predicting ball rebound parameters using inbound spin ratio, defined as the product of the balls angular velocity and radius divided by the tangential velocity of the balls' centre of mass. Inbound spin ratio was unable to predict the rebound parameters however as these were dependent on inbound velocity and angle. It was concluded however that a ball can either (1) slide, (2) slide and then over-spin, or (3) slide, over-spin and then roll, when impacting a surface. When sliding throughout impact the balls tangential velocity decreases and topspin increases. Rolling occurs when the tangential velocity of the ball is equal to the tangential velocity at the surface. Over-spinning occurs when the ball spins faster than it is rolling.

2.7 Ball Degradation

The importance of degradation of tennis balls and its subsequent impact on the game is not underestimated by the tennis community. Balls are subjected to a wear test prior to approval by the ITF and professional tournaments usually replace the six balls in play after nine games of use. These measures are in place to ensure the balls used are fit for purpose throughout the duration of their use. It was noted in 2003 that the ITF did not specify any characteristics of the ball relating to durability in the approval process (Miller and Messner 2003). Consequently, it was not known how long an approved ball

would retain its performance characteristics and remain within the laws of the game. This prompted the ITF to investigate changes in ball properties caused by use and possible laboratory-based wearing techniques (Spurr and Capel-Davies 2007), culminating in the introduction of the degradation test as part of the ball approval process.

2.7.1 Core

Steele *et al.* (2006a) investigated changes to the rubber core with repeated impacts. A wear rig was used to fire balls at approximately $30 \text{ m}\cdot\text{s}^{-1}$ with two oblique impacts, one against a racket string bed and one against a rigid surface. Variation in the standard error meant no definitive conclusions could be drawn. The results perhaps further highlight the inherent variability found when impacting a ball with a rigid surface, as mentioned by Spurr and Capel-Davies (2007). Cubitt and Bramley (2006) also investigated the effect of repeated impacts at given speeds on bounce height. With a launch speed of 60 mph, bounce height was found to decrease by 2% after 20 impacts and 4% after 40 impacts. It is not possible however to determine what percentage, if any, of this change is due to pressure loss or changes in material properties.

Pressure loss

Steele *et al.* (2006a) investigated internal pressure loss through three months of natural ageing. After three months, the internal pressure had significantly decreased although was still significantly higher than atmospheric pressure. The rate of pressure loss decreased over time due to the decreasing pressure gradient between the inside and outside of the ball with time. Differences were found between the dynamic COR and the time spent naturally ageing. Balls that had been aged for up to three months had similar COR whereas balls aged for over six months were found to have a significantly lower COR, and corresponding bounce height, indicating increased energy losses on impact. Both forward and return deformation was seen to increase significantly, further highlighting the effect of pressure loss.

Cubitt and Bramley (2006) studied the effect of leaving balls in ambient pressure for a fourteen day period, exposing three new and three used balls to ambient pressure. The average bounce height of the new and used balls was measured although negligible difference was found between them with respect to time, which agrees with the results of Steele *et al.* (2006a) for balls naturally aged for less than three months. The bounce height of the ball is determined by the properties of the materials used to construct the core and the felt, as well as the internal pressure. It has been claimed that the bounce height test produces inherently variable results that are likely to hide any small changes

in properties (Capel-Davies and Miller 2003, Spurr and Capel-Davies 2007). Consequently, the bounce height test appears inadequate for assessing internal pressure loss, particularly if the balls have been exposed to atmospheric pressure for less than three months. Similarly, it was not stated whether or not the balls were pre-compressed prior to testing, a further factor influencing the validity of the results.

Previous studies have used punctured tennis balls to approximate the effects of pressure loss (Goodwill and Haake 2001, Haake *et al.* 2003). When measuring properties over time using the ITF approval tests the greatest rate of change occurs in the first 30 days from opening (Steele 2006). After three weeks, the results of the bounce height test fall outside of the specification set by the ITF. The internal pressure of the ball also remains considerably higher than atmospheric pressure after 180 days indicating punctured balls are not an accurate representation of balls naturally aged for six months.

2.7.2 Felt

Mass loss

The cloth used in the construction of the ball has been shown to degrade at different rates (Steele *et al.* 2006a). Needle felt showed significantly less mass loss through 500 impacts than sateen weave felt although this is contradictory to the findings of Capel-Davies and Miller (2003). The differences however are likely to be specific to the wear mechanism, impact velocity or brand of ball tested.

The effect of repeated racket impacts was analysed by firing a ball against a rigidly clamped racket string bed using an air cannon (Steele *et al.* 2006a). Ball speed had the most noticeable effect on mass loss whilst the tension of the strings made no significant difference. The type of string also had an effect on mass loss.

Fuzziness

Most investigations focusing on wear have used the approval tests to highlight the effects of wear over time. Steele (2006) however created a method to objectively measure the fuzziness of a given tennis ball. An algorithm was developed to measure the roughness of the balls surface from 12 digital images. The metric was found to be accurate to ± 0.0866 mm and correlated strongly to performance and perception data (Steele *et al.* 2006b). This algorithm allows for the objective assessment of the condition of the felt compared to the previous method of subjectively assessing felt condition. Good agreement was found between the metric, player perception and ball performance

data. Results generated from the Digital Fuzziness Metric (DFM) were compared against drag coefficient, highlighting the state of the felt and its degree of degradation.

Wear caused by time in flight has also been investigated in terms of mass loss and fuzziness (Steele 2006). Having been exposed to a wind tunnel for two hours with wind speeds ranging from 0-40 m·s⁻¹ and spin rates from 0-3000 rpm it was suggested that higher spin rates increase fuzziness however mass loss was negligible.

2.8 Tennis Ball Technology

A range of sports balls are inflated with air, thus requiring air retention properties to maintain the playing characteristics of the ball. Many larger sports balls, such as soccer balls and basketballs can be re-inflated through use of a valve embedded within the construction of the ball, however this solution is not applicable to tennis balls.

With regards to tennis several attempts have been made to reduce air leakage, with many of the rubber-related and gas-related factors affecting permeability investigated. Reed and Thomas (1988) improved air retention through use of larger halogenated gas molecules. Tetrafluoromethane (CF₄) and sulphur hexafluoride (SF₆) were found to permeate through tennis ball compound rubber far slower than air. Halogenated gases are costly compared to air and altered the acoustic properties of the ball, producing a noticeable 'ping' on impact. Mixing the halogenated gas with air in a ratio of 1:1 was not only found to reduce the change in acoustic properties but would also reduce the cost of production. The authors suggested that it was possible for the hardness of balls containing 100% CF₄ to increase. This increase was thought to be due to an increase in internal pressure as air was able to permeate into the ball faster than CF₄ could permeate out. How much the gas influenced the properties of the rubber (such as set) and whether or not the balls were pre-compressed are not known, consequently it is impossible to determine to what degree the authors' conclusions are correct.

Swedish company Tretorn introduced the 'Micro X' a pressureless ball whereby the core is filled with elastomeric closed cell microspheres (Expancel, AkzoNobel). The aim of the Micro X is to replicate the playing characteristics of a pressurised ball whilst eradicating air leakage. The micro cells are between 15-150 µm in size and add between 1-3 g in mass to the ball. The microspheres can be incorporated into the ball in pre-expanded form or in unexpanded pellet form, which can then be expanded in-situ during the manufacturing process (Friel and Hall 2000).

Tretorn have also attempted to improve the pressure retention of pressurised balls through use of a membrane placed between the core and the felt, branded 'Tri-Tec'. The

membrane, developed by BASF, is used on the Serie+ range of Tretorn balls although there is no information as to the effectiveness of the membrane at minimising permeation of air out of the ball.

The Wilson Double Core is a further example of attempting to reduce pressure loss. A nanoparticle elastomeric barrier coating, developed by InMat LLC, was applied to the inside of the core to slow the permeation of gas through the ball, thus prolonging the playable life. The coating consisted of exfoliated vermiculite nanoparticles dispersed within a butyl rubber suspension. Exfoliated vermiculite was used due to its high aspect ratio, allowing the barrier coating to remain thin (and therefore lightweight) whilst forming a tortuous path for diffusing gas molecules. Butyl rubber was used to allow the barrier coating to stretch by up to 20% without damage. This is important due to the high deformations that occur when a tennis ball impacts with a surface or racket at high speed. It is claimed that the barrier coating enables the tennis balls to maintain pressure for between 9-12 months after removal from a pressurised environment (Goldberg *et al.* 2002a, 2002b).

Spalding acquired a patent allowing the use of a membrane and valve combination to reduce air leakage from sports balls, branded 'Neverflat'. The valve is initially capped, and an elastomeric membrane provides the inner most layer of construction. A mixture of air and a large molecule low permeability gas (most likely a halogenated gas) is used to inflate the ball during manufacture (O'Neil *et al.* 2012). Neverflat is used by Spalding in basketballs, soccer balls, volleyballs and American footballs and a one-year warranty is offered for balls that need to be re-inflated within a year, provided the valve cap remains intact. On loss of the valve cap and re-inflation entirely with air the ball behaves like any other sports ball with a standard valve, requiring regular re-inflation.

The cloth has seen much less scientific focus with respect to technical innovations, with the only notable innovation being that of 'Hydroguard' (Slazenger), being a treatment of the cloth to reduce moisture absorption. The treated cloth was shown by Steele (2006) to adsorb significantly less water than standard satin weave and needle cloth.

2.9 Finite Element Analysis

2.9.1 Finite Element Method

Finite element analysis (FEA) allows for the approximation of complex physical problems through use of the finite element method (FEM). FEM is a numerical method which divides a continuum into a mesh of discrete elements, connected by nodes with a finite number of degrees of freedom (Cook 1995). The material properties of the

physical bodies within the model are assigned, along with prescribed boundary conditions and external loads to form a representation of the physical problem. Finite element software typically contains different solving algorithms for static and dynamic problems.

The computational efficiency in dealing with dynamic, non-linear, complex contact events makes an explicit solver a more appropriate option than implicit solvers for modelling non-linear, high-speed impacts as seen in tennis and other sports ball impact scenarios (Prior 1994). In an explicit analysis the time increments are sufficiently small that accelerations are deemed constant between iterations, enabling accurate simulations in a computationally inexpensive manner. Explicit solvers have been utilised multiple times to model sports ball impacts (Cordingley 2002, Goodwill *et al.* 2005, Price 2005, Holmes 2008, Allen 2009, Smith and Duris 2009, Sissler 2012, Hanson 2014).

2.10 Material Modelling

A material model is a constitutive equation and corresponding set of material parameters, which are utilised by finite element software to predict material behaviour. Deformation modelling analyses the deformation response of a polymer as a function of applied load (Bergström 2015). The purpose of the material parameters is to predict the multi-dimensional material behaviour based on data collected from relatively simple experimental tests. Often, material models are required to predict the non-linear, rate-dependent, viscoelastic properties of elastomeric and polymeric materials. This can be achieved through hyperelastic models, hyperelastic models in conjunction with viscoelastic models, and viscoplasticity models.

2.10.1 Hyperelastic Material Modelling

Established hyperelastic material models, available as standard in most commercial FE software, assume the material is non-linear, nearly incompressible and (in most cases) isotropic. Constitutive models are usually phenomenological or micromechanical in nature. Independently, hyperelastic models are 'elastic' in nature in that the unloading response is equal and opposite to the loading response. Additional model parameters or material models are required to capture the viscoelastic properties of the material (hysteresis, creep, stress relaxation).

The governing parameters of micromechanical models relate, to some degree, the physical structure of the material to the macroscopic mechanical behaviour (Steinmann *et al.* 2012). The approach relates the distribution of the end-to-end length of the molecular chains to the number of links in the chain and the length of each link. When

deformation is applied, the chain structure stretches, and the configurational entropy decreases as the structure becomes more ordered. The structures configurational entropy is reflected in terms of principal stretches from which the elastic strain energy function is derived (Treloar 1975, Boyce and Arruda 2000).

The phenomenological approach describes the macroscopic nature of materials as continua and is mainly concerned with the fitting of mathematical equations, to experimental data. These equations usually take the form of a polynomial formulated in terms of strain invariants or principal stretches (Steinmann *et al.* 2012). The underlying microscopic structure of the material however, bears no relevance to the mechanism of deformation. Instead the response of the material is related to the strain energy density, which is only dependent on the upon the deformation gradient (Holzapfel 2000). They are not however, capable of relating the mechanism of deformation to the underlying microscopic structure of the material.

Hyperelastic materials are described in terms of their strain energy potential (W), which defines the strain energy stored in the material per unit reference volume for a given applied strain. The hyperelastic material models all assume that the materials are isotropic, nonlinear and nearly incompressible. The strain energy potential is defined in terms of strain invariants (I_1 , I_2 and J) and corresponding principal stretches (λ_1 , λ_2 , λ_3) whereby:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2,$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2,$$

$$J = \lambda_1\lambda_2\lambda_3$$

Where:

$$\lambda_i = 1 + \varepsilon_i$$

Hence:

$$W = W(I_1, I_2, J)$$

A selection come as standard in FE software with the ability to calibrate against test data. The following hyperelastic models are available in Abaqus; polynomial, reduced polynomial, Ogden, Arruda-Boyce, Van der Waals and Marlow models. Utilisation of these models is relatively simple, with no scripting or external software required, in addition to being capable of obtaining accurate results. Model choice can depend on the

available test data as different models require different test data to be numerically stable across different deformation modes.

2.10.2 Viscoelastic Material Modelling

Viscoelastic material models are typically used in conjunction with linear elastic and hyperelastic material models when applied to finite element simulations, such that the hyperelastic model represents the elastic behaviour of the material and the viscoelastic material model represents the materials' time-dependent behaviour. The simplest way to model the viscous effects of polymeric materials is through linear viscoelasticity. The model is based on the rheological representation of the viscous element as a linear spring in series with a linear dashpot, known as the Maxwell Model. The Maxwell model describes an exponentially decaying stress relaxation modulus based on either stress relaxation, creep or dynamic test data. The Maxwell model is equivalent to a single Prony series term, such that a multi-network Maxwell model (run in parallel) is equivalent to a Prony series. A Prony series is similar to the Fourier transform allowing the estimation of frequency, amplitude, phase and damping components of a signal (Bergström 2015).

Linear viscoelasticity is not always able to accurately predict the viscoelastic response of elastomers. This occurs when the material is no longer in the linear range, resulting in non-linear viscoelastic behaviour (Bergström 2015). Linear viscoelasticity is only appropriate within the linear range of the material. The linear range is typically assessed by running a strain amplitude sweep using a DMA machine and determining the maximum amplitude below which the modulus of the material behaves in a linear fashion. More complex models that can capture nonlinear viscoelastic behaviour (e.g. Power Flow model, Bergstrom-Boyce Flow model) are required to better predict the materials non-linear viscoelastic behaviour at large strains. The Power Flow model is an extension to the linear viscoelastic model with the addition of a viscoelastic flow rate, enabling the Payne effect to be captured, as the predicted storage modulus can decrease with increasing strain amplitude.

Experimentally the storage and loss modulus of elastomeric materials are dependent on strain amplitude and frequency, highlighted by the Payne effect (Payne 1962). The linear viscoelastic model predicts constant storage and loss moduli with increasing strain amplitude. As a result, the capability of the linear viscoelastic model is reliant on the modelled test conditions, particularly when large strains are modelled. It is however available within software packages, such as Abaqus, and can be calibrated against creep, stress relaxation or dynamic test data.

2.10.3 Viscoplasticity Material Modelling

Viscoplasticity models are the current pinnacle of polymer modelling, in terms of accuracy and capability in predicting the non-linear, time- and temperature- dependence of polymers. They do however, typically require more experimental data for adequate calibration, can be more numerically expensive and can require additional software components in the form of user subroutines to implement (Bergström 2015). Additional software is available however, to calibrate (MCalibration) and implement (PolyUMod) viscoplasticity models within FE packages, including Abaqus, overcoming the need for user defined scripts and subroutines (Veryst Engineering, Needham, MA).

A number of viscoplasticity models exist such as the Bergström-Boyce (BB) model, Dual Network Fluoropolymer (DNF) model, Three Network (TN) model and the Parallel Network (PN) model, ranging in complexity and flexibility (Bergström and Boyce 1998, Bergström and Hilbert 2005, Bergström and Bischof 2010, Bergström 2015). Typically, viscoplasticity models represent the total stress as a number of springs and dampers positioned either in series or parallel with each other. The BB model, for example, represents the response of the elastomer using two parallel networks A and B, such that the total stress is decomposed into an elastic component and a history dependent component. Network A represents the equilibrium response using the Eight-chain hyperelastic model. Network B represents the time-dependent response of the material using the Eight-chain model in series with a viscoelastic flow element (Figure 2.7).

Figure 2.7 Constitutive representation of the BB material model.

The PN model provides a framework in which to build viscoplasticity models with the user able to build an arbitrary number of parallel networks. Each network consists of an elastic component, represented by elastic or hyperelastic model, and an optional flow component, with the additional option of including damage or failure predictions. The PN

model allows flexibility for the user to design the material model based on the observed behaviours of the material. It is however, more challenging to create an accurate model as a result.

The hyperelastic components of viscoplasticity models are mostly limited to I_1 strain invariants and can therefore be calibrated using only uniaxial test data. The viscous response, be it linear or nonlinear, can be captured by collecting test data at different strain rates, preferably with relaxation 'hold' segments incorporated into the loading and unloading profile of the test method or through DMA (Bergström 2015). A major benefit of viscoplasticity models is the capability to capture both the elastic and viscoelastic properties of a material in a single material definition, rather than having to calibrate individual hyperelastic and viscoelastic components.

2.11 Modelling of Sports Ball Impacts

Multiple examples exist of FE modelling of sports balls, such as soccer balls (Price 2005, Rezaei *et al.* 2011, Hanson 2014), golf balls (Pugh 2011) and softballs (Smith and Duris 2009, Burbank and Smith 2012) to name a few. Tennis balls are no exception and have seen significant attention from researchers (Cordingley 2002, Cordingley *et al.* 2004, Goodwill *et al.* 2005, Allen 2009, Allen *et al.* 2011, Sissler 2012). Cordingley (2002) was the earliest reported use of FEA software that focused specifically on producing an accurate model of a tennis ball impact against a rigid surface. Much of this work investigated optimising model parameters, specifically; discretisation of the sphere, element selection, and meshing techniques to produce accurate and consistent impact models. Initial work of Cordingley and Goodwill *et al.* produced models of tennis balls impacting normally and obliquely with a rigid surface. This work was progressed by Allen and Sissler who investigated impacts with a racket. Felt has been modelled by splitting the properties according to direction. The compressive properties, through the thickness of the felt, has been modelled as a foam, with the in-plane tensile properties modelled with as a hyperelastic material. Sissler (2012) also incorporated the anisotropic properties of the felt in the same way as Price (2005) with the inner carcass of soccer balls.

2.11.1 Modelling Techniques

Cordingley (2002) proposed discretising of the spherical core into an icosahedron, creating 20 equilateral triangular faces on the core surface, from which an even mesh can be defined. A method which was replicated by Price (2005), Sissler (2012), and Hanson (2014) for sports ball modelling. Shell elements are typically desirable over solid

elements due to computational efficiency, however solid elements were utilised by Cordingley (2002), Sissler (2012), Allen (2009) and Goodwill *et al.* (2005). A shell mesh would require too coarse a mesh for a pressurised vessel, such that the dimension of the shell element representing the core thickness would need to be the smallest dimension of the element. To more accurately capture the geometry of the ball and model closely the deformation behaviour during impact, a finer mesh is required, resulting in the use of solid elements. In contrast, shell elements have been utilised in soccer ball modelling where the ratio of thickness to radius is much smaller.

The use of solid elements not only increases computation time, but are susceptible to shear locking and hourglassing. Shear locking can occur in reduced integration solid elements, when subjected to pure bending, an artificial shear stress is induced. This is overcome using second order solid elements (which are more computationally expensive) or first order reduced integration elements.

First order reduced integration elements are susceptible to hourglassing, where bending moments result in the tension on one side of the element being equal and opposite to the compression of the opposite side of the element. Consequently, there is zero strain energy calculated, despite the presence of element deformation. For reduced integration elements with only a single, centrally located integration point zero stress is predicted and countered by the solver through the addition of artificial strain energy. This effect is minimised through use of multiple layers of elements through the thickness of the ball, with as little as two layers of elements proving adequate (Cordingley 2002).

2.11.2 Materials Testing and Modelling

The hyperelastic models used to represent the rubber core were chosen based on availability within the given FE software package and the results of model calibrations. Cordingley (2002) and Sissler (2012) found the reduced polynomial provided the closest fit to test data, whilst Goodwill *et al.* (2005) and Allen utilised the Ogden model. The model chosen is not imperative provided it is capable of replicating the properties of the material under the range of conditions specified. Variation in required test data for calibration and computational efficiency of the model can however, influence the model chosen. The Ogden model, for example, required a tensile, compressive and stress relaxation data for calibration. Cordingley opted for the reduced polynomial model as it was deemed to produce more accurate results than the Ogden, or polynomial models, when calibrated against one type of test data (in this case tensile), since the model has no dependence on the second strain invariant. Hyperelastic models have been commonly used in sports ball FE modelling to define the non-linear properties of

rubberlike materials. Pugh (2011) has investigated the use of more advanced viscoplasticity models to model the component parts of a golf ball. The parallel network model was employed to capture the non-linear time dependent properties of the materials, using a combination of the Yeoh model for the first network and the Neo-Hookean model in series with a Bergstrom-Boyce flow element for the second network. The model was calibrated against compression test data at three different strain rates, highlighting the potential benefits of viscoplasticity models over multiple hyperelastic and viscoelastic model calibrations.

Cordingley (2002) suggested that simulations showed strain-rate dependency of the rubber core material had the greatest influence on core rebound behaviour. Testing of ball core rubber has, thus far, been limited to quasi-static test speeds in literature (Cordingley 2002, Goodwill *et al.* 2005, Allen 2009, Sissler 2012), consequently, the mechanical properties have not been experimentally determined, despite simulations showing strain rates in the region of 300 s^{-1} being present during impact. In addition to strain-rate dependence of rubber, dynamic material properties assessing the dynamic stiffness and viscoelastic properties have also not been measured and recorded in literature. The lack of experimental data surrounding the mechanical properties of ball core rubber has led to two different fundamental approaches to creating an accurate FE model. Cordingley and Sissler assumed an increase in material stiffness due to rate effects and artificially stiffened the test data when calibrating the material model. Energy loss was then accounted for through stiffness dependent Raleigh damping. Goodwill *et al.* and Allen opted for a different approach whereby the quasi-static test data was used to calibrate the hyperelastic material model, with damping accounted for through iteratively tuning Prony series model coefficients, such that experimental ball impact data was matched closely by the FE model.

Despite both approaches being able to accurately match the FE model to experimental data, the tuning process, be it for stiffness or damping, implies the model is highly specific to the given ball and would not necessarily be valid if the material properties of the core are changed, since only the quasi-static uniaxial properties have been determined. Furthermore, it is not possible to deduce what individual effect strain-rate dependence and viscoelastic properties have on ball core performance, as neither modelling method incorporates experimentally determined values of either. To test the applicability of alternative materials, or even the effect strain-rate dependence and viscoelastic properties has on performance, an alternative modelling approach is required that incorporates experimentally determined strain rate dependence and

viscoelastic properties, such that changes in material properties directly influences the simulated performance and does not require re-tuning against test data.

Although challenging to test and simulate, viscoelastic properties have been incorporated into soccer ball modelling through DMA experimental data and the Abaqus viscoelastic material model, providing accurate simulations of impact performance, despite not incorporating high strain rate uniaxial data (Price *et al.* 2008, Hanson 2014). It is not however, as simple as defining a viscoelastic model results in an accurate representation of energy loss and accurate FE model, as previous work on softballs has shown (Smith and Duris 2009). Softballs do however differ from tennis balls in that they are much stiffer and solid rather than hollow. Tennis balls are similar in structure to soccer balls in that they are both thin-walled hollow pressurised spheres, which might imply the approach taken by Price and Hanson is applicable to tennis, provided an accurate assessment of the viscoelastic properties can be determined and implemented.

2.11.3 Modelling Internal Pressure

Pressurisation of hollow sports balls for impact simulation has mostly utilised the uniform pressure method (Cordingley 2002, Goodwill *et al.* 2005, Price 2005, Allen 2009, Rezaei *et al.* 2011, Sissler 2012, Hanson 2014). Cordingley (2002) and Sissler (2012) for tennis ball simulations and Price *et al.* (2008) for soccer ball simulations utilised hydrostatic fluid elements, pressurised through a cavity reference node to apply internal pressure to the sports ball model. The fluid was defined as a pneumatic fluid, following the ideal gas law. Hanson *et al.* (2015) compared the uniform pressure method to the coupled Eulerian-Lagrangian technique (CEL). The CEL method models the fluid-structure interaction and allows for pressure to temporally and spatially vary, diffusing realistically to fill the volume. Differences in results between the two methods could not be placed entirely due to the method of pressurisation, hence it is suggested to use the uniform pressure method for sports ball impacts due to the computational savings on offer.

2.12 Summary of Reviewed Literature

The current manufacture of tennis balls is a relatively long process and involves the use of several chemicals and additives. In addition, scrap material and reject parts are not recyclable, all of which are a direct consequence of producing ball cores from vulcanised natural rubber. Furthermore, the pressure retention capability of ball cores is limited, resulting in a drop off in performance over time, which is a limiting factor in the balls life span.

Degradation, although not limited to pressure loss, is a recognised issue with balls shown to degrade over time and with use, to such an extent the guidelines for ball changes during professional matches are as frequent as every nine games of play. Tennis ball 'technology' has primarily focussed on improving pressure retention capability and exhausted many of the scientific practices used to reduced permeability in rubbers, relating to both the gas and the rubber. The use of larger gas molecules (e.g. SF₆), incorporation of a barrier membrane with high aspect ratio fillers (Wilson Double Core) and replacement of air microspheres (Tretorn Micro X) have been investigated. All of the proposed solutions however, only add to the number of raw materials and/or processes required to manufacture the ball, increasing complexity and costs.

To address issues regarding the manufacture of tennis balls and possibly pressure retention capability, a paradigm shift away from vulcanised rubbers appears necessary. TPEs offer the mechanical performance of elastomers, required for a ball core, combined with plastic processing methods. Consequently, the current need for mastication, compounding and curing could be eliminated, providing a TPE with suitable mechanical properties can be identified.

Current ball core rubber compounds and TPEs display a distinct set of mechanical properties common in elastomeric materials. The stress-strain response is typically non-linear, and materials have been found to exhibit time-dependent viscoelastic behaviour, such that the rate of extension or frequency of oscillation can determine the given response. Given the short duration, large deformation impacts a ball is subjected to, the mechanical properties at high strain rates and viscoelastic properties are of interest. Thus far, maximum reported strains and strain rates present during impact have been deduced from finite element simulations. Neither the high strain rate mechanical properties or viscoelastic properties of current ball core rubber been reported, which given they contribute to some degree to ball performance would appear necessary to compare alternative TPE materials against in a standardised and representative manner.

To assess and compare the properties of current rubbers and TPEs the service range of the material during representative conditions needs to be established and used to propose a standardised test procedure, against which the isolated material properties can be compared. Since reported material strains and strain rates have only been simulated, physical measurement of these properties during representative impacts would provide further evidence of the properties observed during use. The properties of rubber, particularly at high strain rate however, are not always simple to measure. The

desired strain rates determine the most appropriate test equipment and has been seen to require bespoke test rigs or complex systems to achieve the desired results.

FE modelling is an appropriate tool for predicting the performance of current and alternative ball core materials during impact. FEA has been utilised many times to model the impact performance of sports balls, including tennis. Simulation is advantageous, initially at least, for comparing impact performance without the cost and time implications of large-scale physical prototyping and experimental assessment. Models for the application of assessing potential alternative materials are however required to be driven purely by experimentally determined material definitions, such that the accuracy of the model is not determined by a manual tuning process. This way, a TPE material can be assessed and modelled prior to physical prototyping and impact testing, with the aim of minimising the demand for physical prototypes.

The impact performance of tennis balls is governed by the global stiffness response, to which the felt, core and internal pressure all contribute. COR, contact time, contact force and deformation are the measures typically used to assess impact performance. Although the behaviour of the constituent elements that make up a tennis ball are complex, the test standards enforced on tennis ball are relatively strict, limiting the acceptable range of material properties for whereby the ball conforms to the specification. Any new ball would be required to adhere to and pass the ITF ball approval process for it to be used in an ITF regulated event.

Chapter 3. Characterisation of Ball Impact Conditions in Professional Tennis

3.1 Chapter Overview

Ball tracking data from professional tennis tournaments, played across the major court surfaces, was assessed to establish the impact conditions a ball is subjected to during play. The number of impacts a ball is subjected to is determined and the impact speed and angles assessed, where possible, to inform future laboratory-based impact, degradation testing and the possible need for testing to be court surface specific.

3.2 Introduction

When assessing current and potential alternative materials for tennis ball cores it is important cover the range of properties experienced during use. The impact conditions determine the levels of strains and strain rates experienced, thus the response of the material. Limited assessment of ball impact conditions has been conducted, relating either to typical impact conditions or the number of impacts that occur over a ball's lifespan. As a result, knowledge of the impact conditions experienced by the ball are limited and it is not known whether the conditions vary with court surface.

Elements of what a tennis ball endures during its lifespan in professional tennis have been determined. Reid *et al.* (2016) utilised ball tracking data from the Australian Open (2012-2014) comparing aspects of the men's and women's game. Serve statistics were the subject of the largest differences between the sexes. Additionally, this study highlighted the volume of information present in ball tracking data that would be difficult and / or time consuming to obtain using video based notational analysis techniques. Notational analysis techniques have been used to assess rally length (O' Donoghue and Ingram 2001) and strokes per game at the 2003 US Open (Johnson and McHugh 2006). Three-dimensional high speed video analysis techniques have also been applied to measure racket and ball parameters during top spin forehand strokes (Choppin *et al.* 2009, 2011). This method was limited however, by a small capture volume (2 m³ capture volume on the baseline).

Ball spin rates has received the most attention, there was a conscious effort from the tennis community to monitor ball spin rates and ensure greatly increasing spin rates were not adversely affecting the nature of the game (Goodwill *et al.* 2007, Kelley *et al.*

2009). Choppin *et al.* (2011) measured ball and racket parameters at the 2006 Wimbledon qualifying tournament in order to replicate typical values for a baseline top spin forehand shot in laboratory testing. Typical spin rates and spin axis for flat, slice and kick serves have also been investigated (Sakurai *et al.* 2013).

There is however, no comprehensive assessment of the impact conditions experienced by the ball, from which representative materials characterisation testing can be deduced. Nor if these conditions vary with court surface, implying a possible need to design surface specific tennis balls.

Ball degradation is an issue that tennis brands have looked to address, predominantly in the form of improving pressure retention and to a lesser extent felt wear, with the release of products such as the Wilson Double Core and Tretorn Micro X. Ball degradation has also received attention from the ITF as it has been acknowledged that balls may fall out of specification during use if the initial properties were close to the allowable limits when approval tested (Capel-Davies and Miller 2003). The ball approval process, conducted by the ITF Technical Commission, was developed to ensure a minimum standard and consistency in ball performance. Balls must be approved annually, a list of which is published by the ITF (ITF 2016), and the mass, size, rebound, deformation and durability of the ball are scrutinised against the standard tests defined in the ball approval specification (ITF 2017b).

The ITF durability test reflects typical ball change policy (6 new balls for the warm up and first 7 games and every 9 games thereafter) and sets out to determine if the ball in question can withstand the demands of nine games of professional tennis (Spurr and Capel-Davies 2007). The test was established based on research into the properties of worn, unworn, new and used tennis balls, as well as investigating different methods to replicate changes in mass, rebound height and deformation in the laboratory (Capel-Davies and Miller 2003, Spurr and Capel-Davies 2007). The test itself is twofold; 20 normal impacts at $40 \text{ m}\cdot\text{s}^{-1}$ against a rigid surface to replicate softening, and two minutes of artificial felt wearing to replicate felt loss. Post-wear regime results for mass, size, rebound and deformation are compared to the initial test results for the balls in question and a maximum allowable change is defined (ITF 2015). The ball approval process is not surface-specific although it does accommodate for use at altitude and on different paced courts. Slight differences in specification are defined as type 1 (fast), 2 (medium), 3 (slow) and high-altitude balls designed for use slow, medium and fast-paced courts respectively. Although the approved ball list is dominated by type 2 balls (with very few

type 1 and type 3 approved balls) (ITF 2016), it is commonplace to see brands market balls as clay-specific or suitable for all court surfaces.

The ITF durability test fulfils its intended purpose of ensuring that manufactured balls meet the basic quality levels and minimum standards for ITF accreditation. However, a binary pass-fail test can only assess the degree of degradation against nine games of use. This is ineffective if the level of use is less than or greater than the correlated value as the test is not representative of the ball in use. The ITF test, therefore, is not effective at determining degradation of ball performance over time, nor is it able to assess how long a ball remains within specification, due to its binary nature. While the ITF test has proven effective for maintaining minimum ball standards, it is unable to assess degradation in ball performance with use, across multiple surfaces and at representative impact speeds and angles.

Changes in material composition (felt and rubber), normal impact forces, contact distance and speeds are all relevant factors in tennis ball wear (Steele 2006) and are determined by a combination of the pre-impact conditions (speed, angle and spin) and the surface interaction between the ball and court. To achieve an accurate representation of how a ball degrades during play it would appear necessary to simulate these phenomena as close as possible. A ball degradation protocol is therefore needed to determine ball longevity in the modern game. The results could then be used to evaluate ball degradation performance and assess changes in ball design, such as felt composition and new core materials. A new effective ball degradation test would be able to assess how long a ball remains within the approval specification, as well as assess the rate of ball degradation with use, such that current and prototype balls can be directly compared.

Analysis of ball impact conditions and impact frequency would help inform materials characterisation testing, as the range of likely conditions can be established, and standardised testing conditions determined (such as strains and strain rates present). Furthermore, the assessment of impact frequency, in combination with conditions, would enable the development of a representative, court surface specific, durability test against which current and prototype balls can be assessed. As a result, prototype TPE core balls could be directly compared against current balls to validate any potential improvement with respect to degradation.

3.2.1 Aims & Objectives

Aim: determine the impact conditions a ball is subjected to during use to inform lab-based testing of tennis balls and their constituent materials.

Objectives:

- Determine the speed and angles at which impacts take place.
- Assess the frequency and type of impacts a ball is subjected to during play.
- Evaluate in-play measures against the ITF durability test as a means of assessing ball longevity.

3.3 Methodology

Ball tracking data collected by the automatic line-calling system (Hawk-Eye Innovations Ltd., Basingstoke, UK) from the following events were analysed;

- ATP 250 Thailand Open 2011-13 (hard court (HC), indoor, male event);
- ATP 500 Gerry Weber Open 2011-13 (grass court (GC), outdoor, male event);
- Roland Garros French Open 2011-14 (clay court, outdoor, male (MC) and female (WC)).

The Hawk-Eye data analysed spanned all rounds of each event although men's and women's clay court data was limited to matches played on the two show courts, Court Phillipe Chatrier and Court Suzanne Lenglen. All the matches analysed were best of three set matches, apart from men's clay court matches which were best of five sets. Men's and women's clay data also comprised of an additional year (2014). The Hawk-eye system is calibrated to the dimensions of the court, utilising ten cameras (operating at 50-60 Hz) and corresponding software to track the three-dimensional Cartesian coordinates of the ball with respect to time. The system is officially accredited by the ITF (with a mean reported error of 2.6 mm (Hawk-Eye Innovations 2015)) however it was not used as an officiating aid at Roland Garros; instead umpires checked the marks left on the surface by the ball to determine contentious line calls.

Figure 3.1 Example .trj file of a contested point.

Each point had a file (.trj) containing the ball tracking information (Figure 3.1) which was processed using a custom Matlab (Mathworks, Natick, MA) script. File nomenclature allowed the determination of the set, game and serve number (1st or 2nd) enabling the frequency of different impact events to be determined. The information contained enabled the reconstruction of ball position with respect to time, from which ball velocity was derived in the global X, Y and Z axes. Ball position and speed were calculated at an arbitrary frequency of 1000 Hz in aid of three-dimensional visualisation. Serves (1st and 2nd), racket impacts (not including serves) and surface impacts were then isolated and the corresponding ball speed and, for surface impacts, angle pre-impact and post-impact were calculated. Ball speed on impact with the surface and racket were taken from the end point of the trajectories immediately pre and post where impact occurred; the specific value was calculated from the first derivative of ball position with respect to time. Surface impact angle was calculated using the dot product between the surface normal and the resultant velocity vector at the end of the trajectory (Figure 3.2). Change in either ball speed or impact angle were defined as the post-impact value minus the pre-impact value. Checks were made to ensure the ball contacting the net were not counted as racket impacts. The data was split in terms of the type of impact (serve, racket impact & surface impact) which enabled ball speed for serves, surface impacts and racket impacts and impact angle for surface impacts to be analysed. The mean number of impacts per ball over nine games were deduced on a per match basis from the total number of the given impact scenario and the total number of games. The mean per surface was calculated in the knowledge that six balls were in play for a period of nine games for each event.

Figure 3.2 Schematic of a ball-surface impact showing angles measured.

Checks were made to ensure the serve was the initial trajectory in each file. All serves, irrespective of legality, were included in the analysis along with additional surface and racket impacts occurring after the point was won as these contribute to degradation of the balls. Surface impacts were also categorised into impacts post-serve (1st and 2nd), multiple bounce, bounce after net contact and other (including post-groundstroke) for further analysis. It was possible to split serves into first serves and second serves, however it was not possible from ball tracking data alone to classify the type of stroke played such as forehand, backhand, top spin or slice, for example.

3.3.1 Statistical Analysis

The mean frequency of games per match and the mean frequency of first serves, second serves, racket impacts and surface impacts per game were analysed using one-way ANOVA. Per match means for ball speed and impact angle were first tested for normality using the Shapiro-Wilk test, before the per surface distributions were compared using either one-way ANOVA or Kruskal-Wallis non-parametric test, depending on the result of the normality test. The purpose of which was to determine if the distributions differ with court surface. For normally distributed distributions, mean and standard deviation were reported, whereas for non-parametric distributions box plots with the median were reported. Paired comparisons were conducted using the Bonferroni approach. Two-sample Kolmogorov-Smirnov tests were also utilised to compare the distribution of ball speed and impact angle between surfaces using an adjusted alpha value. All Shapiro-Wilk, ANOVA, Kruskal-Wallis and Bonferroni tests were conducted with a significance level, alpha, of 0.01, whereby a significant result was determined when the test statistic was less than alpha. Kolmogorov-Smirnov tests used an adjusted alpha value ($\alpha = 0.01 \div \text{number of comparisons}$), to account for using a two-sample test.

3.4 Results

Table 3.1 Per surface totals (mean per match $\pm$ one standard deviation (SD)), where HC = hard court, GC = grass court, MC = men's clay court and WC = women's clay court.

	HC	GC	MC	WC
Tournaments	3	3	4	4
Courts Covered	1	1	2	2
Match Length (Best of)	3	3	5	3
Matches	65	69	168	161
Games	1,505 (23 $\pm$ 6)	1,528 (22 $\pm$ 7)	5,659 (34 $\pm$ 10)	3,257 (20 $\pm$ 6)
1st Serves	9,790 (151 $\pm$ 44)	9,898 (143 $\pm$ 43)	36,448 (217 $\pm$ 66)	22,058 (137 $\pm$ 44)
2nd Serves	3,367 (52 $\pm$ 18)	3,479 (50 $\pm$ 17)	13,621 (81 $\pm$ 28)	8,071 (50 $\pm$ 18)
Racket Impacts	40,240 (619 $\pm$ 249)	28,003 (406 $\pm$ 134)	150,922 (898 $\pm$ 336)	87,756 (545 $\pm$ 229)
Surface Impacts	52,770 (812 $\pm$ 297)	41,010 (594 $\pm$ 184)	200,707 (1,195 $\pm$ 418)	118,432 (736 $\pm$ 286)

Figure 3.3 Mean number of impacts per ball during nine games of use for each surface, split by impact type.

The mean number of games per match was highest for men's clay court matches at 34 (Table 3.1) and was significantly higher than the remaining data sets (Table 3.2). Clay court data (men's and women's) was comprised of an additional tournament's worth of matches in addition to coverage of two courts rather than one, resulting in the analysis

of approximately 100 more matches for men's and women's clay than hard court or grass court (Table 3.1). Hard court, men's clay and women's clay had a total number of impacts between 105.5 and 107.3 per ball during nine games, of which approximately 52 were impacts with the court, 40 racket impacts, 4 second serves and 10 first serves (Figure 3.3). Mean impacts per ball on grass court were much fewer at 81.7. The mean number of serves was similar to the other surfaces, but there were approximately 12 fewer racket impacts and 13 fewer surface impacts.

Men's maximum first serve speed was in excess of $60 \text{ m}\cdot\text{s}^{-1}$ and represented the condition with the fastest occurring ball speed. Mean first and second serve speed was fastest on grass court (1st: $53.21 \pm 3.87 \text{ m}\cdot\text{s}^{-1}$; 2nd: $44.53 \pm 3.83 \text{ m}\cdot\text{s}^{-1}$) and slowest for women's clay court (1st: $44.36 \pm 3.75 \text{ m}\cdot\text{s}^{-1}$; 2nd: $38.01 \pm 3.45 \text{ m}\cdot\text{s}^{-1}$) (Figure 3.4). Women's clay court mean serve speed was significantly slower than men's results for both first and second serve. All distributions of second serve speeds, other than the comparison between hard court and men's clay, were significantly different (Table 3.2). The range in men's mean serve speed was $1.24 \text{ m}\cdot\text{s}^{-1}$ for first serve and $2.47 \text{ m}\cdot\text{s}^{-1}$ for second serve.

Figure 3.4 a) First serve speed distribution; b) second serve speed distribution; c) mean $\pm$ SD serve speed. Distribution bin size = $1 \text{ m}\cdot\text{s}^{-1}$.

Maximum ball speed for racket impacts were approximately $45 \text{ m}\cdot\text{s}^{-1}$, occurring post impact. Median ball speed pre-racket impact was also fastest on grass court at $12.46 \text{ m}\cdot\text{s}^{-1}$, with a range of $1.22 \text{ m}\cdot\text{s}^{-1}$ to the slowest (women's clay court). Post-racket impact grass court displayed the slowest median speed, resulting in the smallest change in speed (*post*: $30.10 \text{ m}\cdot\text{s}^{-1}$; *change*: $15.87 \text{ m}\cdot\text{s}^{-1}$). The fastest median ball speed post-racket impact was $32.68 \text{ m}\cdot\text{s}^{-1}$ for men's clay court, resulting in the largest change in velocity of $20.65 \text{ m}\cdot\text{s}^{-1}$, a difference in median of $4.78 \text{ m}\cdot\text{s}^{-1}$ to grass court which showed the smallest change in ball speed for racket impacts (Figure 3.5). Only two paired comparisons of ball speed during racket impacts were not significant, both of which were comparing hard court to men's clay court (pre-impact speed and post-impact speed) (Table 3.3). Pre-racket impact ball speed and change in ball speed were the only variables to return significantly different results when assessing the shape of the distributions (Table 3.4).

Figure 3.5 a) Distribution of ball speed pre-racket impact; b) distribution of ball speed post-racket impact; c) distribution of change in ball speed; d) box and whisker plot for ball speed pre-, post- and change for racket impacts. Distribution bin size = $0.25 \text{ m}\cdot\text{s}^{-1}$.

Figure 3.6 a) Distribution of ball speed pre-surface impact; b) distribution of ball speed post-surface impact; c) distribution of change in ball speed; d) box and whisker plot for ball speed pre-, post- and change for surface impacts. Distribution bin size = 0.5 m·s⁻¹ for pre- and post-impact, 0.25 m·s⁻¹ for change in speed.

Median ball speed pre-surface impact ranged by only 0.6 m·s⁻¹ from 20.16 m·s⁻¹ to 20.76 m·s⁻¹. Little variation was also observed for median post-surface impact ball speed (13.37 – 14.30 m·s⁻¹). The ball reduced in speed due on impact by a median of 6.58 m·s⁻¹, 6.53 m·s⁻¹, 6.91 m·s⁻¹ and 7.04 m·s⁻¹ on hard court, grass court, men's clay court and women's clay court respectively (Figure 3.6). Maximum observed ball speeds occurred pre-impact and were similar in magnitude to maximum ball speeds during racket impact. Both considerable slower than the maximum speeds observed during serves.

The bulk of surface impacts had an impact angle less than 40° the surface, the majority of which had an impact angle between 10 - 20°. Mean pre-impact angle was the only variable not deemed to differ significantly between surfaces (Table 3.3). The pre-impact mean ranged by 0.29° from 18.80° on grass court to 19.09° for women's clay court. A greater range was evident for post-impact angle (2.91°) from 21.41° on grass court to 24.34° for women's clay court. All surfaces exhibited a mean increase in angle (i.e. steeper) post-impact compared to pre-impact. Grass court displayed the smallest mean change in angle of 2.63° with women's clay court displaying the largest at 5.25°, a difference between surfaces of 2.62° (Figure 3.7). Change in angle results were further analysed to investigate the cause of the large peak between 0-0.2° of change, prominent

across all surfaces. Figure 3.8 shows the frequency distribution by impact type for this range.

Figure 3.7 a) Distribution of angle pre-surface impact; b) distribution of angle post-surface impact; c) distribution of change in angle; d) Mean $\pm$ SD angle pre-, post- and change for surface impacts. Distribution bin size = 1° for pre- and post-impact, 0.25° for change in angle.

Figure 3.8 Change in angle by impact type where the change in angle is between 0° and 0.2°. Percentage of all impacts where change in angle is between 0° and 0.2° given in brackets in the legend. 'Other' results on secondary axis. Distribution bin size = 0.002°.

Table 3.2 One-way ANOVA results for comparison of mean frequency per match or game. Where games per match is represented by games/match; 'F' is the ANOVA test statistic; 'Sig' is the significance value and 'd' is Cohen's d effect size. '**' denotes a significant result, Paired comparison results between surfaces given in the form 'HC-GC' where HC = hard court, GC = grass court, MC = men's clay court and WC = women's clay court.

	Games / Match		1 st Serves / Game		2 nd Serves / Game		Racket Impacts / Game		Surface Impacts / Game	
	F	Sig	F	Sig	F	Sig	F	Sig	F	Sig
ANOVA Result	$F(3,459) = 97.13$	<.001*	$F(3,459) = 8.37$	<.001*	$F(3,459) = 7.16$	<.001*	$F(3,459) = 32.98$	<.001*	$F(3,459) = 30.53$	<.001*
Paired Comparison	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d
HC - GC	1	0.16	1	0.01	1	0.14	<.001*	1.34	<.001*	1.17
HC - MC	<.001*	1.18	1	0.13	.030	0.43	1	<.01	1	0.07
HC - WC	.055	0.50	.028	0.38	<.001*	0.55	1	0.02	1	0.12
GC - MC	<.001*	1.29	1	0.14	.261	0.32	<.001*	1.49	<.001*	1.39
GC - WC	.483	0.32	.032	0.36	0.007*	0.46	<.001*	1.32	<.001*	1.32
MC - WC	<.001*	1.67	<.001*	0.54	.599	0.18	1	0.02	1	0.06

Table 3.3 Comparison of mean serve, racket impact and surface impact parameters between court surface with paired comparison post-hoc results. ‘Stat’ represents the test statistic; either ‘F’ for one-way ANOVA comparison of means or ‘ χ^2 ’ for Kruskal-Wallis non-parametric comparison of means. ‘Sig’ represents the significance value where ‘*’ denotes a significant result, ‘d’ represents Cohen’s d effect size. Paired comparison results between surfaces given in the form ‘HC-GC’ where HC = hard court, GC = grass court, MC = men’s clay court and WC = women’s clay court.

	Serve Speed				Racket Impact Ball Speed						Surface Impact Ball Speed						Surface Impact Angle					
	1 st Serve		2 nd Serve		Pre-		Post-		Change		Pre-		Post-		Change		Pre-		Post-		Change	
	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig	Stat	Sig
	<i>F</i> = 688.12	<.001*	<i>F</i> = 207.85	<.001*	χ^2 = 244.00	<.001*	χ^2 = 203.33	<.001*	χ^2 = 185.74	<.001*	χ^2 = 190.36	<.001*	χ^2 = 289.04	<.001*	χ^2 = 164.50	<.001*	<i>F</i> = 1.62	.185	<i>F</i> = 167.70	<.001*	<i>F</i> = 479.71	<.001*
Test Result																						
Paired Comparison	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d	Sig	d
HC - GC	.004*	0.61	<.001*	0.96	<.001*	1.53	<.001*	1.35	<.001*	1.73	<.001*	0.67	<.001*	1.01	.048	0.75	-	-	<.001*	1.79	<.001*	2.31
HC - MC	1	0.17	1	0.17	1	0.16	<.001*	0.86	1	0.70	.003*	0.49	1	0.07	<.001*	1.21	-	-	<.001*	1.10	<.001*	1.38
HC - WC	<.001*	4.03	<.001*	1.90	<.001*	1.41	.006*	0.60	<.001*	0.34	<.001*	1.12	<.001*	1.99	<.001*	1.08	-	-	<.001*	1.19	<.001*	1.92
GC - MC	.022	0.43	<.001*	0.94	<.001*	2.11	<.001*	2.17	<.001*	2.57	1	0.30	<.001*	1.23	<.001*	1.90	-	-	<.001*	3.04	<.001*	5.38
GC - WC	<.001*	4.82	<.001*	3.08	<.001*	3.43	<.001*	0.99	<.001*	2.90	<.001*	1.90	<.001*	3.31	<.001*	1.78	-	-	<.001*	2.76	<.001*	5.99
MC - WC	<.001*	4.30	<.001*	2.29	<.001*	1.43	<.001*	1.51	<.001*	0.57	<.001*	1.75	<.001*	2.40	1	0.14	-	-	.011	0.34	<.001*	0.76

Table 3.4 Significance values for two-sample Kolmogorov-Smirnov comparison of distributions (significant results only). Paired comparison results given in the form ‘HC-GC’ where HC = hard court, GC = grass court, MC = men’s clay court and WC = women’s clay court.

Comparison	Racket Impact Ball Speed	
	Pre-	Change
HC - GC	<.001*	-
HC - WC	-	.001*
GC - MC	<.001*	-
GC - WC	-	<.001*
MC - WC	-	.001*

3.5 Discussion

3.5.1 Impact Conditions

This chapter has identified several variables regarding impact conditions the ball experienced during professional tennis matches. Ball tracking data provided a vast data set from which the distribution of ball speed during surface and racket impacts, and impact angle for surface impacts, were deduced. As a result, these parameters can be replicated during laboratory testing to deduce and inform materials characterisation testing procedures. Representative impact testing can be used to determine the range of properties experienced by the constituent materials during use. To ensure the materials characterisation is all encompassing, the most severe impact conditions need to be determined.

The fastest ball velocities were present during first serves, where speeds in excess of $60 \text{ m}\cdot\text{s}^{-1}$ were observed (Figure 3.4). As racket speed and angle, as well as ball spin, could not be deduced from ball tracking alone, the exact impact scenario cannot be completely defined. Pre-impact ball speed for racket impacts peaked at approximately $25 \text{ m}\cdot\text{s}^{-1}$, with some variation with surface, increasing to approximately $45 \text{ m}\cdot\text{s}^{-1}$ post-impact. This would imply serves are generally a more severe impact scenario than standard ground stroke racket impacts, when assessing ball speed.

Surface impacts indicated peak pre-impact ball speed in the region of $45 \text{ m}\cdot\text{s}^{-1}$ and pre-impact angle distributions highlighting very few impacts whereby the angle was steeper than 40° to the surface. Consequently, a minimal number of impacts occur at an angle close to normal with the surface.

A far more common surface impact condition, based on the distributions, would have a ball speed of $20 \text{ m}\cdot\text{s}^{-1}$ at an angle of 19° to the surface given the median ball speed and mean impact angle. The deformation present, and resulting material strain and strain rate, is likely to be significantly lower than at the higher ball speeds present, particularly in serves. As a result, these conditions are of greater interest when determining laboratory testing procedures for determining the range of material properties experienced by a tennis ball.

3.5.2 Differences Between Surfaces

Given that tennis is played predominantly on three different surfaces (hard, grass and clay courts), each with their own properties and nuances. Consequently, it was of

interest to establish if testing and possibly the design of tennis balls could benefit from being surface specific.

The most notable difference between surfaces was the mean number of impacts per ball for nine games of use (Figure 3.3). Analysis of impact frequencies clearly showed the ball is subjected to fewer impacts during its lifespan on grass than it was on hard court or clay (men's or women's). The number of first and second serves were consistent across surfaces, yet the ball was subjected to approximately 25 fewer impacts on grass than hard court or clay court; all of which were racket impacts and surface impacts rather than serves. Table 3.2 highlights the significant differences and large effect sizes between grass court and the remaining surfaces for the number of racket and surface impacts per game. Consequently, rally length on grass court appeared shorter on average than on hard court and clay court (which appear very similar), resulting in shorter points. It also suggests that any given ball should be capable of enduring more games on grass than on hard court or clay, assuming the impact conditions are no more severe.

With regards to how ball speed and impact angle were distributed by surface, statistical tests highlight some trends that appear consistent with visual inspection (Table 3.3). Hard court and men's clay court have the least significant differences, highlighted by paired comparisons, indicating that the distribution of ball speed and impact angle are most similar between these data sets. Consequently, that suggests that there are more differences between grass court results, such that more differences exist between grass court than either hard court or men's clay. First serve ball speed and pre-surface impact angle for men's data had the same distribution (i.e. not significantly different), clearly showing some similarities between the court surfaces.

Women's first serve speed on clay was significantly slower than hard court, grass court and men's clay court results (Table 3.3). Mean first and second serve speed on hard court were both within $0.8 \text{ m}\cdot\text{s}^{-1}$ of the results of Reid *et al.* (2016) albeit the results of this investigation had larger standard deviations, likely a result of Reid *et al.* only including serves hit in play. Second serve speed results were much more variable, with all comparisons, other than hard-court men's clay court comparison, found to have significantly different distributions.

Although the surface has no physical influence on impact between the racket and the ball whilst serving, it may influence serve tactics, resulting in differing speeds and levels of spin. Sakurai *et al.* (2013) identified a clear trade-off between ball spin rate and velocity for different types of serve. This finding could be evident here with players

attempting to maximise the effectiveness of the second serve by opting for faster, flatter serves on grass as this is perceived to be the fastest paced surface on tour (Brody 2003). Different serve strategies may lead to differences in the rate of ball degradation between surfaces.

The distribution of ball speed for racket impacts provided the most significant differences for paired comparison between surfaces, as opposed to serve speed or surface impact balls speed or impact angle. Median post-impact ball speed for hard court ($31.7 \text{ m}\cdot\text{s}^{-1}$) however, was very similar to that of mean groundstroke speed from the Australian Open ($30.9 \pm 1.5 \text{ m}\cdot\text{s}^{-1}$) (Reid *et al.* 2016). Results from Choppin *et al.* (2011) indicated faster post-racket impact ball speed ($33.9 \pm 5.0 \text{ m}\cdot\text{s}^{-1}$) than the median grass court result ($30.1 \text{ m}\cdot\text{s}^{-1}$), albeit standard deviation overlaps the median from this study. The results from Choppin *et al.* (2011) were taken during practice conditions rather than in play and confined to a 2 m^3 capture volume at the baseline, however they were able to measure racket velocity, finding a modal velocity of $28 \text{ m}\cdot\text{s}^{-1}$, ranging from $17\text{-}36 \text{ m}\cdot\text{s}^{-1}$ for male players.

The distribution of ball speed pre-surface impact was found to be the same for hard court and men's clay court, with grass court and women's clay court results deemed to differ significantly. Despite this, the median ball speed pre-surface impact ranged only from $20.2\text{--}20.8 \text{ m}\cdot\text{s}^{-1}$.

Mean pre-impact angle only ranged by 0.29° across surfaces, yet the post-impact value increased to 2.91° (Figure 3.7). Statistical tests supported this finding and revealed no significant difference between pre-impact angle distributions (Table 3.3). Distribution of angle prior to impact is very similar across all court surfaces, yet these distributions become misaligned post-impact, consequently, the ball appeared to interact differently across the major surfaces used in professional tennis.

When assessing the change in angle distribution a large peak was present across all surfaces between 0° and 0.2° of change. Even though the ball having a similar inbound to outbound angle with the surface is not an abstract concept, the nature of the peak appeared somewhat artificial. Figure 3.8 shows all change in angle results within this range of interest as a function of impact type. A low percentage of these impacts were from surface impacts occurring directly from the serve (3.1%) and were from impacts with the surface caused by the ball dropping to the floor after contact with the net (6.4%). A reasonable proportion were from the ball bouncing consecutively with the surface without any contact from a player's racket or the net (23.5%).

The majority (67%) however, termed 'other', are from impacts with the surface from a subsequent groundstroke, indicating many impacts occurred with the surface whereby the change in angle was less than 0.2° . As such a high percentage of impacts fell within this window, combined with visualising the distribution of the peak by impact type, it would appear the result is genuine. It is worth noting that the files analysed are comprised of polynomial curves fitted to the raw tracked points of the ball with time and are not comprised of the raw data itself, which may induce a degree of error. A further investigation using an alternative measurement method may be necessary if a higher level of accuracy was required.

The tangible differences between the distributions analysed for the different court surfaces is dependent on the future use of the results, especially considering the complex shape of some of the distributions (e.g. surface impact ball speed). The statistical analysis has provided confidence in the visual trends apparent when inspecting the data, such as the similarities between hard court and men's clay court. For the purpose of replicating ball impact conditions in the laboratory, variability and control over variables such as ball speed could far outweigh the differences observed between the distributions observed from different surfaces.

3.5.3 Ball Degradation

The results of this investigation indicate the ITF durability test is not representative of play in modern professional tennis. The high velocity impacts defined by the test only involve impacts with a smooth rigid surface, not representative of a surface on which professional tennis is played. The ball is not subjected to any impacts with a racket, be it under serve or groundstroke conditions. Subjecting the ball to 20 impacts is also significantly fewer than the mean number of surface impacts a ball endured on any surface, the least of which was 41 on grass court (Figure 3.3). In total, the mean number of impacts a ball endured during nine games ranged from 82 on grass court to 107 for women's clay court, resulting in a minimum difference of 62 impacts between in-play results and the number defined by the ITF durability test.

The impact speed and angle of pre-surface impact differs significantly between the ITF durability test and the in-play results. The durability test impacts the ball at $40 \text{ m}\cdot\text{s}^{-1}$, normal to the target surface. Figure 3.7 indicates most surface impacts (92%) have a pre-impact angle between $10\text{-}30^\circ$. Similarly, Figure 3.6 shows most surface impacts (84%) have a pre-impact speed less than $30 \text{ m}\cdot\text{s}^{-1}$. There are however a small proportion of impacts where the impact speed is in the region of $40 \text{ m}\cdot\text{s}^{-1}$. The high speed of these impacts would suggest they represent the first impact with the surface after the ball has

been served, therefore, the angle at which these are occurring will be much less than the normal impacts used in the ITF durability test.

These differences between the ITF durability test and in-play results are likely to arise from the need to produce the minimum acceptable levels of degradation in a controlled, short and concise manner. After all the test is designed to produce a known level of degradation and output a binary pass-fail result, it is not designed to replicate play itself, nor be able to determine ball quality over a set period of real play. For the same reasons this investigation has established that the ITF durability test should not be used to evaluate ball degradation performance, indicating a new test is required to assess ball longevity and rate of degradation in a manner that correlates to modern professional play.

The differences in results comparing ball speed and impact angle across the major surfaces used in professional tennis indicate that any new degradation test may benefit from being specifically adapted to the desired surface. This is most prevalent if the surface in question is grass, as the racket and surface impact frequencies were found to be significantly less than that on hard court and clay court. In turn, this appears to slightly affect the distribution of ball speed on impact as serves and bounces directly after serves have a larger representation than they do on hard court or clay court, warranting the possible need for a surface-specific degradation test.

It is proposed a new degradation test is required to enable the assessment of ball longevity and rate of ball degradation with use, correlated to professional play. Consequently, it is deemed that the new test must better replicate the impact conditions experienced during play than the ITF durability test, whilst offering a test length in terms of number of games rather than a pass-fail result. The proposed test should try to match, as closely as possible, the court surface, number of impacts of each impact type and the corresponding impact conditions for ball speed and impact angle. Table 3.5 shows a proposed new durability test whereby the ball is subjected to impact frequencies and conditions matching that found in this investigation. For simplicity, the ball speed and surface impact angle have been stated as a mean $\pm$ one standard deviation. To replicate the conditions seen in-play more precisely, the distributions of ball speed and impact angle could be represented more closely. Racket impacts would most likely be replicated using a fixed racket and ball cannon. Ball speed post-racket impact and ball speed and angle post-surface impact could be monitored and compared to the corresponding results of this investigation to validate if the test is matching that of in-play.

Table 3.5 Proposed new durability test conditions based on analysis of impact conditions and frequencies, equating to nine games of use. Includes the number of impacts and the mean ball speed (± 1 standard deviation) for each impact type and mean impact angle for surface impacts.

Impact Type	Surface-Specific Test Conditions			
	Hard Court	Grass Court	Clay Court (Men's)	Clay Court (Women's)
1st Serve: Post-impact ball speed	10 @ 52 $\pm$ 5 m·s ⁻¹	10 @ 53 $\pm$ 4 m·s ⁻¹	10 @ 52 $\pm$ 4 m·s ⁻¹	10 @ 44 $\pm$ 4 m·s ⁻¹
2nd Serve: Post-impact ball speed	3 @ 42 $\pm$ 4 m·s ⁻¹	3 @ 45 $\pm$ 4 m·s ⁻¹	4 @ 43 $\pm$ 4 m·s ⁻¹	4 @ 38 $\pm$ 3 m·s ⁻¹
Racket Impacts: Pre-impact ball speed	40 @ 13 $\pm$ 4 m·s ⁻¹	28 @ 14 $\pm$ 6 m·s ⁻¹	40 @ 13 $\pm$ 4 m·s ⁻¹	40 @ 12 $\pm$ 3 m·s ⁻¹
Surface Impacts: Pre-impact ball speed and impact angle	52 @ 22 $\pm$ 8 m·s ⁻¹	41 @ 22 $\pm$ 9 m·s ⁻¹	53 @ 22 $\pm$ 8 m·s ⁻¹	54 @ 21 $\pm$ 6 m·s ⁻¹
	19° $\pm$ 8°	19° $\pm$ 9°	19° $\pm$ 8°	19° $\pm$ 9°
Total	105	82	107	108

3.5.4 Limitations

The findings of this investigation are not without limitations, one of which is the nature of the data set whereby it is specific to only one event per surface, played over consecutive years. It is therefore not possible to assume that these results are truly representative of tennis played on each surface in general. While the events were all professional tour events, they were not all of the same standing or match length, which could influence the quality of the players on show as not all players compete in all events. There is also the matter of players prioritising events, such as grand slams, over smaller less prestigious events. Furthermore, the data will naturally be skewed towards the individuals who contributed most to the data set. As the event followed a knockout style, players who made it furthest through the event were involved in more matches, resulting in an over-representation of those players. Similarly, the same players did not necessarily compete in the event across all years, nor did they necessarily compete across all the events analysed, adding variation to the results. The type of data analysed is also limited in what can be extracted from it. Parameters relating to the racket (speed, impact angle and contact location) and ball spin could not be determined from ball tracking alone.

Future investigations should look to determine the frequency distribution of racket parameters (impact velocity and angle) and ball spin during professional play. The addition of these parameters to the ball speed and angles analysed in this investigation

would provide a more complete picture of what a ball endures during play; enabling a more representative degradation test and assessment of the strains and strain rates present when conducting laboratory-based impact testing to inform characterisation of material properties. It may be possible to accurately estimate racket and ball spin parameters based on pre- and post-impact speed and angle of the ball, removing the need for further data capture using alternative measurement systems.

3.6 Conclusions

Ball tracking information has been utilised to derive novel information surrounding the frequency and conditions of impacts a ball is subjected to during nine games of professional tennis. The mean number of impacts a ball was subjected to during nine games of professional play was 105, 82, 107 and 108 for men's hard court, grass court, clay court and women's clay court matches respectively. Approximately 50% of impacts were with the surface, with serves accounting for 13-14 impacts. Grass court matches saw a reduction in racket impacts and surface impacts which indicated reduced rally length compared to the hard court and clay court data. On average, the ball impacted the surface with a speed of $20 \text{ m}\cdot\text{s}^{-1}$ at an angle of 19° from the surface.

The results of this body of work can be used to infer more representative impact testing of tennis balls in the laboratory, given both the frequency and distribution of ball speed and surface impact angle. To determine the range of material properties representative of ball impacts during play, aspects such as peak ball speeds and angle are of interest to test the more severe impact cases. Ball speeds during serves were found to be in excess of $60 \text{ m}\cdot\text{s}^{-1}$ and impact angles with the surface as steep as 40° .

Ball tracking information has been utilised to determine that the ITF degradation test is ineffective for assessing the degradation performance of tennis balls except, when determining basic quality levels and minimum standards for ITF accreditation. The ITF test is an accelerated aging test, consequently, it cannot be used to determine ball longevity and rate of degradation in a manner that correlates to modern professional play, warranting the need for a new degradation test. Furthermore, a new representative degradation test could be used to assess the performance of alternative ball designs against simulated play.

Comparison of ball speed and impact angles across the four major court surfaces used in professional tennis indicated that any new degradation test may benefit from being specific to the court surface. Particularly if the surface of interest is grass due to the fewer impacts the ball was subjected to and the effect of the different composition of

serves, racket impact and surface impacts on the distribution of ball speed during pre- and post-impact.

A new degradation test protocol, specific to each surface, has been proposed based on the findings of this investigation. The proposed test is correlated against in-play findings enabling the assessment of ball longevity and rate of degradation. The new test may benefit further from the addition of ball spin racket trajectory information.

Chapter 4. Determination of Ball Core Strain & Strain Rate During Impact

4.1 Chapter Overview

The strains and strain rates present during impact of the ball core against a rigid surface were investigated. GOM digital image correlation software was utilised to measure strains and strain rates across a range of impact conditions. A select number conditions were compared to previous FE modelling techniques to determine a range of strains and strain rates that occur during impact to inform material characterisation test conditions.

4.2 Introduction

Chapter 3 established typical inbound impact conditions the ball experienced, particularly with the surface, during professional tennis matches. This knowledge enables the replication of typical impact conditions in the laboratory. Previous efforts to understand the behaviour of the ball core in isolation has focussed, almost exclusively, on normal impacts with a rigid surface as a means of validating FE simulations (Cordingley 2002, Allen 2009, Sissler 2012). These simulations require characterisation of the mechanical behaviour of the rubber compound to predict the behaviour of the modelled ball core. Characterisation of ball core materials has so far been limited to quasi-static tensile, compressive and stress relaxation testing. The issue with current test methods are the speeds and consequent achievable strain rates for testing. Typically, tensile tests have been conducted with a crosshead speed in the range of 50-999 mm·min⁻¹ (Sissler 2012). Elastomeric materials are known to exhibit strain rate dependent behaviour, with stiffness increasing with increasing strain rate, particularly at high strain rates (Bergström and Boyce 2000, Hoo Fatt and Bekar 2004, Roland 2006). When defining material behaviour, of current or potential alternative materials, for FE simulations it is desirable to match the properties of the material when subjected to the strains and strain rates observed during use.

Previous modelling techniques have utilised an iterative process comparing artificial stiffening of stress-strain data and high-speed video footage and force trace data of impacts to establish a material model providing a realistic representation of the ball during impact (Cordingley 2002, Sissler 2012). In part, this process is a result of the limitations of available material testing equipment. Only through simulation have maximum strains and strain rates observed during impact been estimated. Cordingley (2002) estimated maximum strains in the region of 0.5 with maximum strain rates in the

region of 300 s^{-1} . Allen (2009) recorded maximum strains in the region of 0.3 for an impact against a rigid surface at $30 \text{ m}\cdot\text{s}^{-1}$.

Traditional strain measurement devices such as strain gauges and extensometers do not lend themselves to high velocity ball impacts due to the associated connected electronics and possible alterations in deformation caused by the sensor being in contact with the surface. Optical strain measurement techniques utilising digital image correlation (DIC), such as GOM Correlate, provides a means of three-dimensional surface strain measurement utilising multiple cameras. GOM Correlate identifies stochastic image information, referred to as facets, by evaluating the grey values present within the facet. Optimal facets have a distinct and equally distributed pattern, with maximum possible contrast in grey values within the facet (GOM 2016). DIC could be employed to measure the strains and strain rates present during ball impacts and used to inform material characterisation testing; in turn, enabling FE modelling to utilise material modelling techniques based on experimental data rather than artificial stiffening of quasi-static behaviour. Although not used to measure strain, GOM has been successfully implemented in a sporting context to measure golf ball and clubhead velocity (Leach *et al.* 2017).

4.2.1 Aims & Objectives

Aim: to establish the strains and strain rates experienced by tennis ball cores during impact, whereby the impact conditions are representative of professional play, to inform materials characterisation test conditions.

Objectives:

- Experimentally measure strain and strain rate during impact using digital image correlation software.
- Utilise previous work on FE simulations of ball core impacts to predict strain and strain rate during normal impact.
- Inform necessary material characterisation test conditions.

4.3 Methodology: Strain Measurement During Impact

4.3.1 Equipment Set-up

Data collection took place in the ball impact laboratory at the Sports Technology Institute at Loughborough University. Ball cores were fired at a steel impact plate (15 mm thick) using a pneumatic cannon. The impact plate was angled accordingly to achieve the desired impact angles, measured using a digital protractor. Two Photron Fastcam SA1.1

(Photron, San Diego, CA) high-speed cameras were positioned approximately 0.75 m from the impact plate. The cameras were fixed to a beam, fitted to a tripod, and directed towards the centre of the impact plate, such that the angle between the cameras was approximately 24°. Light gates were positioned at the end of the barrel and connected to a frequency counter, used to monitor ball speed and trigger video recording (Figure 4.1).

Figure 4.1 Left: Plan view of lab set-up; Right: Photo of lab set-up.

4.3.2 GOM

Both high-speed video cameras were fitted with 85 mm fixed focal length lenses (Zeiss planar T 1.4/85 mm ZF 2). The cameras operated as a pair to track the ball core during impact with the steel plate. Each camera was set-up for a capture volume around the impact plate of 275 × 275 × 275 mm. The high-speed video cameras were synchronised and set to trigger as the ball passed through the light gates on leaving the barrel of the cannon. Images were recorded at a frequency of 12,000 Hz; the resolution was adjusted depending on impact angle to maximise pixel coverage of the ball (Table 4.1). Shutter speed ranged from 1/71,000 to 1/74,000 to prevent image blur while allowing sufficient light exposure. The aperture of the lenses was set at f/5.6, as recommended by GOM, and additional lighting, in the form of two flicker free ARRISUN 1,200 W lights (ARRI AG, Munich, Germany) were utilised to resolve the problem of reduced light exposure.

Table 4.1 Camera settings for each impact angle.

Impact Angle (°)	Shutter Speed (s)	Resolution (Pixels)
18.9	1/74,000	1,024 × 496
27.6	1/74,000	1,024 × 496
40	1/71,000	960 × 528
90	1/74,000	1,024 × 496

The volume of interest was calibrated in accordance with GOM instructions by capturing a series of images at full resolution (1024 × 1024 pixels) of a specific calibration object in multiple positions and orientations within the capture volume. The calibration object used was a GOM calibration panel, 200 mm × 160 mm in size. Calibration images were imported into GOM software (GOM Correlate Professional 2017) and processed automatically given the specific details of the image sensor and calibration object used. A calibration file was produced, and results given as to the quality of the calibration. As the cameras were repositioned to record at each impact angle, a separate calibration was performed for each, the results of which are given in Table 4.2. All calibrations were deemed successful as the quoted calibration deviation was less than 0.05 pixels, the maximum specified by GOM. The intersection deviation provided further confidence in the quality of the calibration and experimental set-up. The intersection deviation represents the nonconformity in the identification of points in each camera image. The value should be consistent across all frames and in the region of 0.3 pixels or less.

Table 4.2 GOM calibration results

Impact Angle (°)	Calibration Deviation	Measuring Volume
18.9	0.020 pixels	275 × 275 × 275 mm
27.6	0.020 pixels	275 × 275 × 275 mm
40	0.019 pixels	275 × 280 × 280 mm
90	0.019 pixels	280 × 280 × 280 mm

4.3.3 Details of Ball Core Preparation

Pressurised (Wilson US Open) and pressureless ball cores (Wilson Championship) were used in the investigation. Twenty of each ball type were used, five balls per impact angle. Each ball was subjected to one impact per test speed, resulting in five impacts per core, all at one given impact angle.

Figure 4.2 Ball preparation. Left: pressurised ball core; Right: pressureless ball core

A stochastic pattern was applied to the cores using a black permanent marker to enable the GOM software to detect a surface and measure variables of interest (Figure 4.2).

Due to the colour of the rubber compound of the pressureless ball cores, it was necessary to spray paint the cores matte white prior to applying the pattern. This ensured a large enough contrast between the light and dark areas of the pattern for the GOM software to detect. The load-extension profiles for painted and non-painted samples highlighted the application of paint did not affect the stiffness of the rubber (Figure 4.3). The tests were conducted on a uniaxial test frame (Instron ElectroPuls E3000), which limited the test to quasi-static test speeds as high strain rate testing equipment was not available. Five repeats of each sample were tested (ISO 37 type 1 sample size) at a speed of $400 \text{ mm} \cdot \text{min}^{-1}$.

Figure 4.3 Effect of paint on the load-extension response pressureless ball core rubber (mean of five repeats displayed for painted and non-painted tensile samples).

Prior to testing, each ball core was subject to pre-conditioning as defined by the ITF ball approval process. Each core was acclimatised at 20°C and 60% humidity for 24 hours prior to testing using a climate chamber (Alpha 190H, Design Environmental Ltd.). The ball cores were then subjected to nine pre-compressions by 2.54 cm sequentially through three perpendicular axes using an Instron ElectroPuls E3000 dynamic test system to remove set in the rubber.

4.3.4 Data Collection

In total 200 impacts were recorded, 100 each for both the pressurised and pressureless ball cores. Four impact angles and five ball speeds were selected (Table 4.3), predominantly based on the findings of Chapter 3, to best replicate the impact conditions experienced during professional play. Each angle was tested independently on different days due to the time taken to position the impact plate, high-speed video cameras and calibrate GOM. The temperature of the laboratory across all testing days was between

20°C and 21°C. As a result, a new set of five pressurised and pressureless ball cores were assigned to each test angle. Each ball core was subjected to one impact at each test speed for a solitary impact angle, resulting in a maximum of five impacts per ball core. This ensured minimal degradation in ball performance and, predominantly, to ensure optimal pattern quality for the GOM software to process, as this could be inhibited by marks and smudges to the stochastic pattern. The nature of the pneumatic cannon meant the randomisation of ball speed to minimise order effects was not feasible. As a result, each ball was tested from the fastest test speed to the slowest. This was deemed the most suitable compromise as it ensured the stochastic pattern was in the best condition under the most testing conditions (least impact frames and largest deformation) for the GOM software to process. Image capture was triggered as the ball passed through the light gates. The high-speed videos were cropped to exclude frames where the ball was not present and saved in individual folders for each camera as 8-bit TIFF images.

Table 4.3 Impact condition selection

Impact Angle (°)	Reasoning
18.9	Mean surface impact angle
27.6	Mean surface impact angle plus one standard deviation
40	Intermediate case between surface impact angles results and normal impacts
90	Simplified impact case, comparable to FE simulations
Ball Speed (m·s⁻¹)	
13.7	Mean pre-surface impact ball speed minus one standard deviation
22.1	Mean pre-surface impact ball speed
30.5	Mean pre-surface impact ball speed plus one standard deviation
43.1	Mean second serve ball speed (Men's)
52.5	Mean 1st serve ball speed (Men's)

4.3.5 Data Processing

Images were imported into GOM Correlate Professional 2017 where a surface component was created. Maximal surface coverage was achieved with a facet size in the region of 15 pixels and point difference in the region of 10 pixels, whereby a facet is a square section of the image and the point difference is the distance in pixels between the centre points of adjacent facets. This was coherent with GOM recommendations whereby the point distance should be approximately two thirds the facet size. An image approximately five frames prior to impact was selected as the reference frame (Figure 4.4), against which all other strain calculations were compared. It is therefore assumed

the ball core was under no strain at this point in time. This assumption was deemed valid due to the non-contact nature of the pneumatic cannon, subjecting the ball to minimal deformation on firing. Furthermore, on visual inspection and through use of GOM, no significant change in ball shape or surface strain was apparent prior to impact. Major and minor nominal strain, major and minor nominal strain rate and velocity were calculated in GOM and exported as CSV files. The frame of first and last contact with the impact plate were noted and used to define the frames of interest when analysing strain and strain rate.

Each CSV file contained the three-dimensional coordinates of each surface point alongside the strain, strain rate and velocity values for an individual frame. The number of surface points exported per file varied depending on how much of the surface defined in the reference frame was visible in that particular frame. Results were further processed in Matlab R2015b (Mathworks, Natick, MA) to assess the frequency distribution of strain and strain rate during impact.

Major and minor strain are calculated by GOM using the principal axis transformation of the strain tensor. The principal axis transformation provides eigenvalues and eigenvectors for the new orthonormal basis of the strain tensor. The larger eigenvalue defines the major strain and the smaller eigenvalue defines the minor strain, with the direction of the strains defined by the corresponding eigenvectors. Major and minor strain rate are defined as the change in corresponding strain divided by the change in time.

To determine the maximum absolute strain for each element of the surface, the major and minor strains of the element were compared to determine the greatest absolute strain value. The value of greatest magnitude was selected for strain and the corresponding strain rate value was also selected based on the magnitude of the major and minor strain. The mean and standard deviation of strain and strain rate were calculated across all elements for all frames during impact, across all repeats. The frequency distribution of strain and strain rate was also assessed. The mean velocity of all elements of the surface prior to impact was used to define the pre-impact ball velocity.

Figure 4.4 Surface coverage of major strain ($30.5 \text{ m}\cdot\text{s}^{-1}$, 90°) pre- and during impact.

4.4 Results: Physical Measurement During Impact

To determine the ideal test conditions for material characterisation testing it is necessary to understand the strains and strain rates present under the most extreme impact conditions, to endeavour to capture the materials behaviour within that range. Consequently, a select number of the impact conditions tested have been analysed in detail in this chapter. The following subset of test conditions described in Table 4.3 were selected for analysis: 18° at $22.1 \text{ m}\cdot\text{s}^{-1}$; 40° at $52.5 \text{ m}\cdot\text{s}^{-1}$; 90° at $30.5 \text{ m}\cdot\text{s}^{-1}$, 90° at $52.5 \text{ m}\cdot\text{s}^{-1}$.

The largest strains during impact occurred for impacts at 40° and $52.5 \text{ m}\cdot\text{s}^{-1}$, warranting further analysis. Similarly, the largest strain rates during impact (in terms of magnitude) occurred for impacts at 90° and $52.5 \text{ m}\cdot\text{s}^{-1}$. Impacts tested at 90° with either of the two fastest impact speeds ($43.1 \text{ m}\cdot\text{s}^{-1}$, $52.5 \text{ m}\cdot\text{s}^{-1}$) were found to lose surface tracking during impact, resulting in one or more frames where GOM was unable to compute a surface. This occurred for both pressurised and pressureless ball cores due to the extreme levels of deformation, as shown in Figure 4.5. The 90° and $30.5 \text{ m}\cdot\text{s}^{-1}$ impact condition was selected to include impacts at 90° whereby the surface of the ball was tracked throughout impact as opposed to partially tracked. The impact condition representing the mean surface impact angle and ball speed found during professional play (Chapter 3) was included to provide a benchmark against a more typical impact.

Figure 4.5 Example impact frames with loss of surface tracking for impacts at $52.5 \text{ m}\cdot\text{s}^{-1}$ and 90° . Left: pressurised; Right: pressureless.

4.4.1 Impact Ball Speed

Ball speed prior to impact was dependent on the air pressure setting within the pneumatic cannon system, rather than setting ball speed directly. The pressure within the system drifts resulting in alteration of the air pressure prior to each impact, consequently, the actual ball speed on impact varied. Mean ball speed for each speed and angle impact combination are given in Table 4.4. The maximum difference in mean ball speed to desired ball speed was $4.6 \text{ m}\cdot\text{s}^{-1}$ with a mean difference of $-0.6 \pm 1.4 \text{ m}\cdot\text{s}^{-1}$ when considering all impact conditions.

Table 4.4 Mean pre-impact ball speed $\pm$ one standard deviation (SD) for impact conditions of interest.

Angle ($^\circ$)	Desired Ball Speed ($\text{m}\cdot\text{s}^{-1}$)	Pressurised	Pressureless
		Mean $\pm$ SD	Mean $\pm$ SD
18.9	22.1	22.9 ± 1.1	23.1 ± 1.2
40	52.5	54.8 ± 0.4	53.0 ± 0.6
90	30.5	30.4 ± 0.7	32.1 ± 1.2
90	52.5	52.1 ± 0.6	51.5 ± 1.7

4.4.2 Impact Strain

The range of strain present increased with impact angle and impact velocity. The strains of greatest magnitude occurred for impacts at 90° and $52.5 \text{ m}\cdot\text{s}^{-1}$ for both pressurised and pressureless ball cores. The smallest range of strain occurred for impacts at 18.9° with in impact velocity of $22.1 \text{ m}\cdot\text{s}^{-1}$. Over 95% of strain measured was distributed between -0.1 and 0.1 strain. The remaining impact conditions at higher impact angles and faster impact speeds are more widely distributed (Figure 4.6). Figure 4.6 also highlights a higher percentage of tensile (positive) strain is present than compressive (negative) strain, as well as being present to a greater degree at strains to a greater magnitude. For example, 8.4% of strain on average was distributed between 0.2 and 0.3

strain, compared to 2.1% for strains between -0.3 and -0.2 when assessing all distributions except that of impacts at 18.9° and 22.1 m·s⁻¹.

Figure 4.6 Normalised distribution of strain during impact (bin size = 0.025). Left: pressurised; Right: pressureless.

4.4.3 Impact Strain Rate

In general, the range of strain rate during impact increased as impact speed at a given angle increased. Likewise, for a given impact speed the maximum observed strain rate increases in magnitude as the impact angle tends towards normal. Consequently, the strain rate of greatest magnitude occurred for impacts at 90° and 52.5 m·s⁻¹ for both pressurised and pressureless ball cores (up to -800 s⁻¹). The impact case representing the mean surface impact conditions (18.9°, 22.1 m·s⁻¹) was distributed evenly either side of zero. All other impact conditions were shifted in the negative direction, with negative strain rates accounting for around 60% of the distribution (Figure 4.7). No impact condition was found to have greater than 1% of the distribution whereby the strain rate was greater in absolute magnitude than 800 s⁻¹.

Figure 4.7 Distribution of strain rate during impact (bin size = 25). Left: pressurised; Right: pressureless.

4.5 Methodology: Simulation of strain and strain rate during impact

FE simulations were also used to assess the strains and strain rates present during the impact of tennis ball cores against a rigid plate. Impacts were modelled normal to the impact plate at impact speeds of $30.5 \text{ m}\cdot\text{s}^{-1}$ and $52.5 \text{ m}\cdot\text{s}^{-1}$ to match the impact conditions tested experimentally and analysed with GOM Correlate. Oblique impacts were not modelled as the core impact models produced by Cordingley and Sissler, that formed the basis of this body of work, were not validated against experimental data for oblique impacts.

Cordingley and Sissler produced similar ball core simulations utilising the same discretised geometry, mesh, element type and material model. The core was discretised into a spherical icosahedron as this shape was shown to exhibit rotational symmetry and uniform impact characteristics (Cordingley 2002). The mesh was formed of two layers of six-node first order reduced integration triangular wedge elements (C3D6R elements). In total, the mesh was formed of 5,760 elements (Figure 4.8).

Figure 4.8 Ball core discretisation and mesh

First order reduced integration elements are favourable as they do not suffer from shear locking and they are computationally efficient, compared to alternatives such as second order fully integrated elements (Abaqus 2016a). They can however suffer from hour glassing when subjected to pure bending, whereby the tensile strain on one face of the element is equal to the compressive strain on the opposite face of the element, resulting in zero strain as the neutral axis will be located through the integration point (Figure 4.9). Consequently, for this bending case the software will predict zero stress, leaving the system out of balance which must be countered by the addition of artificial strain energy. Hour glassing has been shown to be greatly reduced by introducing a second layer of elements through the thickness of the core as the top layer of elements undergoes mostly tensile loading whilst the inner layer is subject mainly to compressive loading (Cordingley 2002).

Figure 4.9 Hourglassing associated with reduced integration elements

Pressurisation of the ball core was achieved by creating a fluid cavity using the inside surface of the ball core and a cavity reference point positioned at the centre of the cavity within the ball core. The air used to pressurise the ball core was defined as a pneumatic fluid as follows (Abaqus 2016b):

- Ideal gas molecular weight $0.0289 \text{ kg}\cdot\text{mol}^{-1}$
- Absolute zero (θ^Z): -293.15 K (such that the temperature of the simulation is equivalent to 20°C)
- Universal gas constant: $8.314 \text{ J}\cdot\text{mol}^{-1}$

- Molar heat capacity:

$$c_p = a + b(\theta - \theta^Z) + c(\theta - \theta^Z)^2 + d(\theta - \theta^Z)^3 + \frac{e}{(\theta - \theta^Z)^2}$$

Where: $a = 28.11$, $b = 1.976 \times 10^{-3}$, $c = 4.802 \times 10^{-6}$, $d = -1.966 \times 10^{-9}$, $e = 0.0 \text{ J}\cdot\text{mol}^{-1}$

- θ = temperature (K)

The fluid cavity utilised the uniform pressure method to define the pressure within the cavity using equations representing the thermodynamic properties of air, whereby at each point in time during the simulation the internal pressure was identical at each point of the inner surface of the cavity. The internal pressure was set to 83 kPa as described by Sissler (2012).

Since different rubber compounds were modelled by Cordingley and Sissler, the material model defining the behaviour of the rubber differed between the two models. Both selected the second order reduced polynomial hyperelastic material model with β damping, however the model coefficients varied between the two (Figure 4.10). The β damping factor introduces a damping stress proportional to the total strain rate and is interpreted as defining viscous material damping. Both generated the material coefficients from quasi-static tensile test data of the rubber before tuning both the stiffness related parameter (C10) and β damping value until the model accurately represented high speed video footage of impacts across a range of impact velocities.

Figure 4.10 Hyperelastic material models of Cordingley & Sissler.

Coefficients of the reduced polynomial model quoted by Cordingley and Sissler were inputted directly into Abaqus however, due to possible changes to the software over time the exact β damping value for Cordingley's model was no longer applicable and could not be used. A new damping value was determined by assessing the effect of changing the damping value on the coefficient of restitution (COR) when modelled as a normal impact at $35 \text{ m}\cdot\text{s}^{-1}$. The COR was compared to experimental results from Cordingley until the COR was deemed comparable (Figure 4.11). A damping coefficient of 1.165×10^{-4} was selected for Cordingley's updated model. COR was considered the most appropriate determinant as it is effectively a measure of energy loss in the system and a consequence of the viscoelastic behaviour of the material. Once a damping value had been determined the model was run at a range of inbound ball velocities from $10 \text{ m}\cdot\text{s}^{-1}$ to $55 \text{ m}\cdot\text{s}^{-1}$ in $5 \text{ m}\cdot\text{s}^{-1}$ intervals and the COR compared to the results of the original model to ensure a good degree of agreement between original and updated material models (Figure 4.11).

Figure 4.11 (A) Effect of changing β damping value of the COR of a $35 \text{ m}\cdot\text{s}^{-1}$ normal impact. (B) COR response of updated model compared to original material model results.

Table 4.5 Reduced polynomial material model coefficients used in FE simulations.

Material Model Coefficients	Cordingley	Sissler
Reduced Polynomial - C10	1.75×10^{-6}	2.5×10^{-6}
Reduced Polynomial - C20	-3.9×10^{-4}	303,067
β Damping	1.165×10^{-4}	1×10^{-4}

The simulations comprised of four steps other than the initial definition step; pressurisation, hold, apply velocity and impact. During the pressurisation step the internal pressure inside the cavity was increased to 83 kPa, defined by Sissler (2012), using a smooth step ramp. The hold step was utilised to allow the core to expand and the internal pressure to stabilise prior to impact. The apply velocity step set the ball core

moving towards the impact plate at the desired velocity and the impact step allowed for the ball core to impact the plate.

In total four simulations were run using the two material models at two different impact speeds ($30.5 \text{ m}\cdot\text{s}^{-1}$; $52.5 \text{ m}\cdot\text{s}^{-1}$), all with an impact angle of 90° to the surface. The simulations provided a direct comparison to the GOM analysis with equivalent impact conditions. Minimum and maximum nominal strain values for all elements of the ball were exported at a frequency of 12,000 Hz, the same as the high-speed video recording used to capture the GOM data. Matlab was used to calculate the minimum and maximum principal strain rate of each element. The maximum absolute principal strain and corresponding strain rate were then determined. The frequency distribution of strain and strain rate were assessed using the same frequency bins used to analyse the GOM data to act as a direct comparison.

4.6 Results (FE)

At $30.5 \text{ m}\cdot\text{s}^{-1}$ the largest percentage of strain ($\approx 39\%$) occurred between 0 and 0.1 strain. At $52.5 \text{ m}\cdot\text{s}^{-1}$ strain was more evenly distributed between - 0.1 to 0, and 0 to 0.1, with each range accounting for approximately 27%. The higher impact speed had a wider distribution of strain with larger percentages accounting for strain greater in magnitude than - 0.1 and 0.3 strain (Figure 4.12). No simulation had greater than 1% strain above 0.4 or below - 0.3 strain. Overall, approximately 60% of strain was positive in value, representing tensile strain.

The majority of strain rate ($> 60\%$) was distributed between - 100 s^{-1} and 100 s^{-1} for simulations at $30.5 \text{ m}\cdot\text{s}^{-1}$. The same range for impacts at $52.5 \text{ m}\cdot\text{s}^{-1}$ accounted for approximately 42%. The trend of the distribution is similar to that of strain whereby the higher velocity simulations have a lower peak value and wider distribution than the equivalent lower velocity impact (Figure 4.12). No simulation had more than 1% of the distribution greater in magnitude than - 500 s^{-1} and 500 s^{-1} strain rate. The distribution of strain rate was shifted slightly towards the negative direction with an average of 53% of the distribution less than zero.

Figure 4.12 FE simulation results; (A) normalised strain distribution (bin size = 0.25); (B) normalised strain rate distribution (bin size = 25).

4.6.1 Comparison to GOM Strain Analysis

Comparison of GOM surface strain analysis to FE simulations produced highly comparable strain mapping during normal impacts at 30.5 m·s⁻¹ and 52.5 m·s⁻¹ (Figure 4.13 & Figure 4.14). Both the magnitude and pattern of strain across the surface of the ball were similar for measured GOM results to FE simulations. The deformation profile of the simulated impacts followed closely the profile of the ball core in the images, particularly during the compression phase of impact as the ball was being squashed against the plate. The benefits of both FE and GOM are highlighted. Physical measurement provided a suitable means of validating FE simulations, while FE simulations offer complete of the whole ball core, without the loss of tracking seen with physical measurement (Figure 4.14).

Figure 4.13 Comparison of GOM strain analysis and FE simulations for a $30.5 \text{ m}\cdot\text{s}^{-1}$ impact. Surface strain map and distribution.

Figure 4.14 Comparison of GOM strain analysis and FE simulations for a $52.5 \text{ m}\cdot\text{s}^{-1}$ impact. Surface strain map and distribution.

4.7 Discussion

For the purpose of materials characterisation, it is necessary to understand the strains and strain rates experienced by the material during the intended conditions of use to truly understand the behaviour of the material. The results of this investigation highlight that both compressive and tensile strains are experienced during impact with a rigid plate. Regarding maximum strain values, tensile strains above 0.4 were uncommon with frequency distributions highlighting no frequency bin above 0.4 strain containing more than 1% of the distribution. All GOM-analysed impact cases and FE simulations were in agreement with this finding, indicating that material testing of ball core rubber in tension should test to 0.4 strain to encapsulate the range seen during impact.

Experimental impacts of the pressurised ball core at 40° and 90° with an impact ball speed of 52.5 m·s⁻¹ as well as both FE simulations at 52.5 m·s⁻¹ were shown to have in the region of 5% of strain distributed between 0.3 and 0.4, further evidence that 0.4 strain is the minimum desirable strain when trying to encapsulate the tensile behaviour of tennis ball rubber. These findings are slightly lower than the findings of Cordingley (2002) who suggested strains in the region of 0.5 can be observed during impact.

Assessing the observed tensile strain rate, measured by GOM, highlighted all impact conditions other than the mean surface impact condition (18°, 22.1 m·s⁻¹) had around 1% of the distribution between 500 s⁻¹ and 600 s⁻¹, with no frequency bin above 300 s⁻¹ accounting for more than 3.5%. Similar percentages were also observed for FE simulations from 300 s⁻¹ to 600 s⁻¹. Cordingley (2002) reported maximum strain rates during ball core impacts of approximately 300 s⁻¹. Results of both the GOM surface analysis and FE simulations, in combination with the reported value by Cordingley, indicate that tensile strain rates in the region of 600 s⁻¹ are apparent, however to a limited degree (< 1%). The ability to characterise the material at this rate would be optimal, although capturing material behaviour with a strain rate up to and including rates in the region of 300 s⁻¹ would capture the vast majority of tensile strain rates experienced during impact.

Maximum observed compressive strains from GOM analysis suggested strains up to - 0.4 were present for impacts at 90° and 52.5 m·s⁻¹, accounting for around 1% of the distribution. Negligible amounts of strain (< 0.2%) were measured for compressive strains greater in magnitude than - 0.4. Simulation results indicated no frequency bin greater with strain greater in magnitude than - 0.3 accounted for more than 1% of the distribution. Simulation results indicated in the region of 0.5% of strain was between - 0.3 and - 0.4 and only for impacts at 52.5 m·s⁻¹. The results suggest material

characterisation in compression would encapsulate the vast majority (> 95%) of observed compressive strain during impact if tested to strains of - 0.4, whilst testing to strains of - 0.3 may be sufficient depending on the severity of the impact conditions.

Compressive strain rates calculated by GOM were found to account for more than 1% of the distribution for rates up to -800 s^{-1} for impacts at 90° only. For impacts at 40° the maximum compressive strain rate was closer to -700 s^{-1} and for the mean impact condition closer to -200 s^{-1} . Frequency bins between -400 s^{-1} and -800 s^{-1} for the 90° , $52.5 \text{ m}\cdot\text{s}^{-1}$ impact condition account for more than double the percentage of the other impact conditions (10-15%). FE simulation results indicated a narrower distribution of compressive strain rate with frequency bins containing over 1% of the distribution found only up to rates of -500 s^{-1} .

With respect to the maximum strains and strain rates observed during impact both the GOM results and FE simulations appear in good agreement. Similarly, comparisons to literature appear consistent. Goodwill *et al.* (2005) highlighted maximum strain for simulation at $30 \text{ m}\cdot\text{s}^{-1}$ of 0.3, consistent with both simulations at $30.5 \text{ m}\cdot\text{s}^{-1}$, and GOM results for 90° $30.5 \text{ m}\cdot\text{s}^{-1}$, whereby all frequency bins above 0.3 strain contained less than 1% of the distribution. Although the range of values appears similar, the distributions between FE simulations and GOM vary. FE results for strain and strain rate appear normally distributed, whereby increases in impact speed results in a wider distribution range and smaller normalised peak height. GOM distributions for mean surface impact test case (18° , $22.1 \text{ m}\cdot\text{s}^{-1}$) follow a similar trend however, the remaining cases do not. For strain, these distributions have multiple peaks rather than one distinct peak around zero, whilst strain rate distributions are skewed in the negative direction, with negative strain rates accounting for around 60% of the distribution. These differences are likely due to the differences between the nature of the simulations in comparison to GOM. GOM is limited by the surface coverage, which is dependent on camera positions and relative placement. Clearly with one camera pair it is not possible to obtain full surface coverage, particularly as the underside of the ball is obscured by the impact plate. Furthermore, it is only possible to measure parts of the object that are visible, therefore strains through the thickness of the material and on the inside surface of the cavity cannot be measured.

Increased ball coverage could be achieved using additional cameras. A calibration of each camera 'pair' would be required in addition to the calibration of a global reference frame, to which all surface analysis could be transposed and combined to achieve a more complete coverage. This would however greatly increase the time required to

capture and process the data and would require access to multiple high-speed cameras with each pair of cameras having matching lenses.

The GOM reference frame is assumed to be in a state of zero strain, from which all strain computation is referred to. Any residual strain and deformation of the core prior to impact caused by the launch method was minimised through use of a pneumatic cannon. Alternative ball launchers utilising rotating wheels to propel the ball could have been used however they damage the stochastic pattern on the ball due to friction when fired.

In contrast, the simulations have the benefit of estimating strain and strain rate, among other potential parameters of interest (e.g. stress), throughout the entire ball core in three dimensions. The results of the simulation are entirely dependent on an accurate representation of reality in terms of both the boundary conditions placed on the object and the information given to describe the behaviour of the material. The material models used by Cordingley and Sissler utilised β damping rather than attempting to measure and incorporate the viscoelastic properties of the material through use of dynamic mechanical analysis or stress relaxation tests. The damping value is not a measurable parameter of the materials behaviour, more a phenomenological means of achieving a desired outcome.

4.8 Conclusions

This body of work is the first reported example of physical strain and strain rate measurement during the impact of tennis ball cores. DIC provided a useful means of measuring strain and strain rate during impact, which had only previously been assessed through FE simulations. The results of which will be used to inform material characterisation testing when assessing the mechanical properties of ball core rubber, as the range in material behaviour has been evaluated. In turn, enabling materials characterisation testing to be representative of extreme impact conditions experienced during use.

The results of this Chapter have highlighted the range of tensile and compressive strain and strain rate experienced during impact, enabling representative materials characterisation testing. Compressive testing up to strains of - 0.4 at rates up to - 800 s^{-1} and tensile testing up to strains of 0.4 at rates up to 600 s^{-1} is sufficient in capturing the behaviour of the material experienced during a normal impact against a rigid surface with a ball impact speed up to $52.5 \text{ m}\cdot\text{s}^{-1}$.

Both FE simulations and GOM surface analysis have proved effective means of determining the surface strains and strain rates observed during impact, albeit when

deformation becomes too large (90° , above $43.1 \text{ m}\cdot\text{s}^{-1}$) impact frames cannot be computed, leaving no surface measurement. DIC has proved an effective means for validation of FE simulations, capable of providing a comparison across the profile of the ball throughout the duration of impact.

It was also noted that previous FE modelling techniques utilising β damping, were incorporating a non-measurable parameter, more a phenomenological means of achieving a desired outcome; highlighting the benefit of investigating viscoelastic material properties, in conjunction with multi-strain rate materials data to assess core material properties and enable the development of experiment driven FE modelling.

Chapter 5. Characterisation of Tennis Ball Core Rubber

5.1 Chapter Overview

The behaviour of rubber materials used in the production of current pressurised and pressureless tennis ball cores were characterised. The tensile properties from low to high strain rate were assessed using a combination of standard test equipment and a bespoke test rig. DMA was utilised to evaluate the viscoelastic material properties. The characterisation process provides standardised data against which alternative materials can be compared, as well as enabling the development of a test data driven FE model.

5.2 Introduction

Assessment of surface impact strains and strains, in conjunction with previous FE modelling techniques, have provided the range of strains and strain rates observed during ball impacts against a rigid surface. In addition, the application of phenomenological means of incorporating model damping, have highlighted the need to experimentally determine the viscoelastic and multi-strain rate properties of ball core rubber to improve understanding of the material. Furthermore, allowing for a standardised comparison between ball core rubber and potential alternatives as well providing the necessary material properties to produce an experimentally driven FE simulation. Although the properties of elastomeric materials are well understood, the testing of, particularly at high strain rates can prove challenging.

The mechanical properties of vulcanised elastomers are typically non-linear when assessing the load-extension curve of the material. Elastomers are also capable of undergoing large elastic deformations, several times the initial length of the sample, and return to their original shape on release of the applied load. Although capable of recovering to its original shape, unloading of elastomers results in energy loss caused by internal friction, termed hysteresis. Hysteresis is characterised by the loop formed in the load-extension curve during cyclic loading, whereby the area within the loop is equivalent to the energy lost, mostly in the form of heat. Cyclic loading highlights another phenomenon, the Mullins effect, whereby an elastomer experiences a reduction in stiffness during the first few loading cycles indicating a strain history dependence.

Elastomeric materials also exhibit viscoelastic behaviour. Viscoelastic behaviour is a time-dependent mechanical response to external forces that falls between an elastic solid, obeying Hooke's law, and a viscous liquid that obeys Newton's law. When

subjected to an applied stress the sluggish configurational changes to the complex entanglement of long chained molecules results in a lag between the applied stress and imparted strain. This behaviour is strongly dependent on time and temperature, resulting in strain rate dependent behaviour whereby stiffer behaviour is observed with increasing strain rate.

To compare different elastomeric materials, for the purpose of improving performance or reducing cost, it is necessary to characterise the materials under the conditions observed during use. Due to the viscoelastic properties of elastomers the mechanical behaviour can differ drastically due to time, frequency and temperature dependence of the material. Characterisation of the elastic behaviour is typically achieved using a uniaxial screw-based load frame (e.g. Instron 5569), capable of testing a given material in tension and compression, among other modes of deformation. This type of machine is typically limited by a crosshead speed in the region of $50\text{--}1,000\text{ mm}\cdot\text{min}^{-1}$, resulting in a maximum achievable strain rate in the region of 0.5 s^{-1} when testing an ISO 37 type 1 test specimen in tension. Electromagnetic dynamic load frames (e.g. Instron ElectroPuls E3000) have improved capability with respect to strain rate, with oscillations at an amplitude of 16 mm and frequency in the region of 5 Hz possible ($\approx 6\text{ s}^{-1}$ strain rate). Servo-hydraulic test machines (e.g. Instron VHS 8800 High Rate System) are capable of large displacements at speeds in the region of $25\text{ m}\cdot\text{s}^{-1}$ (Roland 2006). They are however very expensive, limited to a handful of institutions and generally are setup to capture substantially higher loads than what would be required to test ball core rubber samples.

Due to the limitations of commercially available load frames, alternative means of capturing large strain, high strain rate behaviour of elastomers have been deduced. High strain rate in tension is typically considered as rates in excess of 10 s^{-1} (Hoo Fatt and Bekar 2004). It is a topic which has received attention since the early 1950s, with investigations into the tensile strength and breaking extension of different rubbers at strain rates as high as 1000 s^{-1} (Villars 1950, Kainradl and Handler 1962). Early high speed tensile testing was limited by non-uniform rates of extension, and complete stress-strain curves were difficult to obtain because computerised data acquisition was not developed at the time (Hoo Fatt and Bekar 2004).

Alongside bespoke test rigs, utilising a drop mass or pendulum mechanism (e.g. (Hoo Fatt and Bekar 2004, Mott *et al.* 2007)), the Split Hopkinson Pressure Bar (SHPB) method has been used to assess the stress-strain behaviour of materials at strain rates in excess of 1000 s^{-1} (Song and Chen 2003). A cylindrical test piece is positioned

between two elastic bars, and a third smaller 'striker' bar is propelled towards the 'incident' bar. The properties of the material are deduced from the reflected and transmitted pulses usually using strain gauges attached to the bars sandwiching the material sample (Roland 2006). Although, usually equipped to test materials compressive behaviour, a tensile version of the SHPB has been used to test silicone rubber at strain rates between 750 s^{-1} and 1200 s^{-1} (Shim *et al.* 2004).

Thus far, tennis ball cores materials have seen limited characterisation, all of which has been conducted at quasi-static speeds using conventional load frames (Cordingley 2002, Allen 2009, Sissler 2012). No such testing has been conducted to establish the properties and behaviour of ball core materials at rates representative of the impact conditions seen during play. Only Allen (2009) and Goodwill *et al.* (2005) have explored the compressive behaviour of the material and there are no cases reported in literature whereby the viscoelastic properties of tennis ball core material have been characterised experimentally. Soccer ball modelling has seen the successful incorporation of viscoelastic material properties based on the results of DMA testing (Price 2005, Hanson 2014). DMA has also been utilised to characterise the behaviour of polyurethane foam used in softballs (Smith and Duris 2009).

Tensile and dynamic materials characterisation were the focus of this chapter to assess the materials behaviour and provide the foundation for finite element simulations. Despite GOM surface strain analysis highlighting the presence of compressive strains, materials were not characterised in the compressive deformation mode in this chapter.

The ISO test standard for compressive testing of rubber (BS ISO 7743) states a cylindrical sample 29 mm in diameter and 12.5 mm in thickness with flat parallel surfaces (British Standards Institution 2011). Although testing need not directly follow a standard, the samples of ball core are three to four times thinner than the standard test piece, as well as being dome shaped due to being cut from a sphere. Consequently, obtaining accurate and reliable compressive test data is more challenging.

Additionally, modelling of tennis balls has highlighted the propagation of lateral hoop strains, which follow a circular equator around the circumference of the ball parallel to the impact surface. These strains place the outer surface of the ball in tension, making the tensile mode the dominant mode of deformation (Cordingley *et al.* 2004). Furthermore, previous examples of sports ball FE modelling have not incorporated compressive data when calibrating material models, yet have been successful in producing accurate sports ball impact simulations (Cordingley 2002, Price 2005, Holmes 2008, Sissler 2012, Hanson 2014). Consequently, dynamic material characterisation

was prioritised alongside tensile data at the expense of compression testing when characterising ball core rubber.

5.2.1 Research Aims & Objectives

The aims of this chapter are to:

- Capture the elastic material behaviour of ball core rubber at the strains and strain rates observed during impact at in-game speeds and angles; based on the results of Chapter 4.
- Establish the viscoelastic properties of ball core rubber when subjected to a range of frequencies.

Objectives:

- Characterise low strain rate tensile material behaviour using commercially available testing equipment.
- Develop a methodology and test rig to assess the high strain rate tensile material behaviour.
- Utilise DMA to assess the viscoelastic properties of the ball core materials.

5.3 Methodology

5.3.1 Low Strain Rate Tensile Testing

Figure 5.1 ElectroPuls E3000 set up with tensile grips. Photron SA1.1 camera to record images of sample extension.

Low strain rate tensile testing was conducted using an Instron ElectroPuls E3000 electromagnetic dynamic test frame, equipped with a 3 kN dynamic load cell (Figure 5.1). Material samples were cut directly from pressurised Wilson U.S. Open and pressureless Wilson Championship ball cores using a die cutter. The cutter produced dumbbell shaped samples in accordance with ISO 37 type 1 sample dimensions, the international standard for determining the tensile stress-strain properties of rubber (British Standards Institution 2012). The gauge length of the test sample, as defined by ISO 37, was 25 mm in length, 6.2 mm wide and thickness equal to that of the ball core wall.

All samples were subject to a pre-conditioning cycle to remove the Mullins effect and produce a consistent material response. A 5 N pre-load was applied to remove the ‘slack’ from the sample, caused by the spherical shape from which it was cut, before the sample was subject to six extensions to 0.5 strain at a frequency of 1 Hz.

During testing the samples were first subjected to a 5 N pre-load, before being extended to a strain in the region of 0.5 and returned to zero strain to record the loading and unloading properties of the material. Testing was conducted at four different frequencies;

0.01 Hz, 0.1 Hz, 1 Hz and 5 Hz. The first three frequencies enabled the material to be assessed over two logarithmic decades in strain rate, whilst the 5 Hz test was the fastest speed the machine could complete the test. The test frequencies equated to strain rates of 0.012; 0.12; 1.2 and 6 s⁻¹. During each test, the sample was cyclically loaded six times at the desired frequency, with the 5th sample used as the result, this allowed for the ElectroPuls to stabilise and produce the desired test displacement and crosshead speed. Five repeats at each test speed were recorded.

Table 5.1 High speed camera settings at each test frequency for low strain rate tensile testing.

Test Frequency (Hz)	Frame Rate (fps)	Shutter Speed (s)
0.01	50	1/1,000
0.1	50	1/1,000
1	1000	1/10,000
5	4000	1/10,000

Nominal stress was measured using the cross-sectional area of the sample, measured with Vernier callipers, and the load through the sample, measured by the ElectroPuls. Strain was measured using DIC software (GOM Correlate Professional 2017). A high-speed video camera (Photron SA1.1) with a 50 mm fixed focal length lens was used to record the deformation of the sample. The frame rate and shutter speed used at each test frequency are described in Table 5.1. A linear scale was used as a calibration object to convert pixel distances to millimetres. The extensometer function within the DIC software was applied to calculate strain, such that the gauge length of the sample was 25 mm as defined by ISO 37. The software could then compute the extension of the gauge length throughout the duration of the test as highlighted in Figure 5.2.

Figure 5.2 GOM extensometer function, showing initial extensometer definition and example of sample elongation.

5.3.2 High Strain Rate Tensile Testing

Figure 5.3 Test set up for high strain rate tensile testing showing test rig position within the drop tower and camera setup.

Tensile testing ball core rubber at strain rates in excess of the capabilities of the ElectroPuls utilised a bespoke test rig, used in conjunction with an Instron 9250HV drop tower impact system (Figure 5.3). The bespoke test rig (Figure 5.4) was formed of an outer rectangular frame, the bottom of which was bolted to the bed of the test area of the drop tower. A second, narrower rectangular frame formed the second part of the rig. The sides of which, made from steel rods, passed through the top beam of the outer frame, such that the inner frame could move up and down freely relative to the outer frame. As with lower speed tensile testing, ISO 37 type 1 specimens were used during testing. The sample was fixed to the top beam of the outer frame and bottom beam of the inner frame such that when the sample was subjected to elongation when the inner frame is pushed downwards the bottom of the outer frame. Sandwiched between the top beam of the outer frame and the component to which the sample was fixed, was the force transducer, used to measure the force through the sample when strained.

Figure 5.4 Test rig for high strain rate tensile testing.

Force measurements were taken using a Brüel & Kjaer Type 8230-003 force transducer. The transducer had a reference sensitivity of 0.2757 mV/N and maximum tensile force of 2,200 N. A Brüel & Kjaer Nexus conditioning amplifier supplied the transducer with a 10 mA power supply and feed the raw signal onto a Picoscope 5000 series oscilloscope. The scope was set to record one million samples over a time period of 1 s, with the voltage range set to ± 200 mV with a resolution of 15 bits. The voltage signal recorded

by the oscilloscope was saved as a MAT file for processing in Matlab. Since the raw signal was not subject to any amplification, 1 mV was equivalent to 1 N.

As was the case with lower strain rate tensile testing using the ElectroPuls, strain was measured using DIC software (GOM Correlate Professional 2017). A single high-speed video camera (Photron SA1.1) fitted with a 50 mm fixed focal length lens was used to record sample elongation. The camera settings for each drop height are defined in Table 5.2. The camera and oscilloscope were triggered simultaneously at the start of each test using a manual trigger switch. The images were imported into the DIC software and the extensometer function was utilised to measure sample strain.

Table 5.2 High speed camera settings applied at each drop height.

Drop Height (cm)	Frame Rate (fps)	Shutter Speed (s)
20	1000	1/10,000
50	4000	1/12,000
70	6000	1/12,000

The drop tower was fitted with a hemispherical end effector and the mass of the drop carriage was 6.8 kg. To increase the strain rate at which the sample was tested the drop height was increased. The drop height was defined as the distance between the top of the rig (with the sample in position) and the bottom of the end effector. The drop height could be artificially increased by spring loading the drop carriage. In total three drop heights were chosen for testing; 20 cm, 50 cm and 70 cm. At each drop height five samples of each ball core material were tested. Prior to testing, the samples were subjected to the same pre-conditioning cycle using the ElectroPuls as the samples used for low strain rate testing, to remove the Mullins effect from the material.

The maximum drop height was limited by the state of the force signal, rather than the capability of the drop tower or the ability to measure sample strain. At higher drop heights and consequent impact speeds the transducer signal was dominated by noise and vibration. The maximum drop height whereby the force transducer signal was deemed satisfactory, was 70 cm and chosen as the largest of the heights tested.

Data Processing

Processing of the force signal and extensometer results from GOM was conducted in Matlab (R1015b). A lowpass Butterworth filter was employed to remove high frequency noise from the force signal; the properties of which were determined by analysing the frequency content at each drop height. The signal was subject to a discrete Fourier transform, to transform the time-based data into frequency-based data. The amplitude

spectrum of the signal (Figure 5.5) was used to determine the cut off frequency for the lowpass filter. A cut off frequency of 200 Hz was deemed suitable, with much of the high frequency noise present at frequencies in excess of 200 Hz for drop heights of 70 cm and lower. The lowpass Butterworth filter was applied to each signal using a zero-phase digital filter Matlab function (“filtfilt”). The stress through the sample could then be calculated by dividing the force by the cross-sectional area of the sample.

Figure 5.5 Frequency content of force readings at different drop heights (pressurised ball core sample).

Examples of raw and filtered force data are presented in Figure 5.6 at four drop heights between 20 cm and 90 cm. At 90 cm significant noise and vibration is present within the force signal as highlighted by the raw force trace (Figure 5.6D) and the frequency content of the amplitude spectrum. Consequently, three drop heights were selected for testing, the maximum of which was 70 cm as the signal noise at this drop height was deemed acceptable.

Figure 5.6 Raw and filtered force signal at different drop heights.

To calculate strain, the high-speed video images were imported into GOM Correlate Professional 2017. A pixel to millimetre conversion scale, based on a calibration image of a linear scale, was applied and the extensometer function was used to define the gauge length of the sample. A start point and a direction were defined on the sample, enabling GOM to produce a virtual extensometer of the desired length (25 mm). The length of the extensometer was calculated throughout the image series in question and was exported as a CSV (comma separated value) file. When imported into Matlab, the extension was converted into strain by dividing the change in length by the original length.

To produce stress-strain curves of each test it was necessary to equate both stress and strain at the same points in time. Since the oscilloscope sampled significantly faster than the high-speed video, the stress with respect to time was interpolated against the strain time values providing a stress and strain for a series of given points in time.

5.3.3 Dynamic Mechanical Analysis

Figure 5.7 Mettler Toledo DMA/sDTA861e machine.

A Mettler Toledo DMA/sDTA861e (Mettler Toledo GmbH, Greifensee, Switzerland) was used to perform frequency sweeps of the ball core rubber samples (Figure 5.7). Tests were performed in the shear mode using circular disc shaped samples with a mean thickness and diameter of 5.78 mm and 1.95 mm for pressurised core and 5.68 mm and 1.98 mm for the pressureless ball core. Five frequency sweeps were performed at three different displacement amplitudes. The first displacement amplitude was within the linear range of the material. This was determined by performing a displacement sweep and assessing the modulus and force reading with respect to displacement. The results of which (Figure 5.8) are used to determine the end of the linear range of the material (Pressurised: 4 μm ; Pressureless: 9 μm). The point at which the modulus begins to drop and the force begins to rise (highlighted by the dashed line) indicate the end of the linear range and determines the displacement amplitude for the test (Fedelich 2011). Two further displacement amplitudes were selected above the linear range (Pressurised: 15 μm and 50 μm ; Pressureless: 20 μm and 50 μm). Frequency sweeps were performed at the defined displacement amplitudes from 0.01 Hz to 600 Hz with 8 steps per decade.

Figure 5.8 A) Force response and B) modulus response of ball core compounds when subjected to a displacement sweep. End of the linear range marked by the dashed line.

5.4 Results

5.4.1 Low Strain Rate Tensile Testing

Figure 5.9 Repeats of low strain rate tensile testing across all strain rates for the pressurised ball core (A) and pressureless ball core rubber (B).

The ElectroPuls enabled tensile testing to a strain magnitude greater than 0.5 strain at strain rates spanning nearly three logarithmic decades between 0.012 – 6 s⁻¹. Figure 5.9 shows the stress strain response of both the pressurised and pressureless ball core rubber compounds. Strain rate dependence is minimal in both across the range in question and only visibly present at strains greater than approximately 0.2 in magnitude. The consistency of response at each strain rate suggests, although small, strain rate dependence is present.

The two rubber compounds exhibit very similar behaviour, typical of vulcanised rubbers. The stiffness of both materials is very similar, particularly at strains less than 0.2. At strains greater than 0.3 the stiffness of the pressureless ball compound drops off slightly in comparison, such that the stress at 0.5 strain is approximately 0.25 MPa lower than the equivalent stress for the pressurised ball core compound. Both compounds exhibit minimal hysteresis, indicating low energy loss and high resiliency as expected for rubbers used in dynamic impact events such as ball impacts. The mean stress-strain response of the materials at each strain rate (Figure 5.10) further emphasises these findings. It is also notable that the increase in stiffness with strain rate appears uniform, particularly for the pressurised ball core rubber.

Figure 5.10 Mean tensile properties at low strain rates for (A) pressurised and (B) pressureless ball core rubber.

5.4.2 High Strain Rate Tensile Testing

Figure 5.11 High strain rate testing results across the range of drop heights. A-B strain versus time; C-D stress vs time; E-F stress-strain response of all repeats; G-H mean stress-strain response. Pressurised and pressureless ball core rubber results presented.

The test rig and drop tower combination provided a consistent, repeatable means for tensile testing dumbbell test specimens at strain rates greater than the capabilities of the ElectroPuls. Figure 5.11 shows the stress and strain response with respect to time

(A-D), highlighting the repeatability of measurement and the effect of increasing drop height on strain rate and material response.

The test method enabled the stress response of the materials to be measured at strains in excess of the desired 0.5 magnitude, with responses up to 0.8 strain possible for the larger drop heights. Both the stress and strain response begin to plateau as the sample either slows until it is no longer extending or the rig reaches its maximum possible extension. This occurs at strains in excess of the magnitude of interest (0.5 strain).

Drop heights of 20 cm, 50 cm and 70 cm resulted in strain rates in the region of 40 s^{-1} , 62 s^{-1} and 84 s^{-1} respectively, covering the majority of the decade between 10 and 100. Figure 5.11 highlights the repeatability of the stress-strain response (E-F) using the test rig and the mean stress-strain response at the tested strain rate (G-H). The pressureless ball core material exhibited very little strain rate dependence across the rates tested. In contrast, the mean stress-strain response of the pressurised ball core compound showed signs of strain rate dependence at strains above 0.1 in magnitude. The lowest strain rate tested (40 s^{-1}) showed reduced stiffness compared to faster strain rates at strains above 0.1 in magnitude.

5.4.3 Combined Tensile Results

The results from combined low and high strain rate testing provided the stress-strain behaviour of ball core rubber materials across nearly four logarithmic decades of strain rate from 0.012 s^{-1} to 84 s^{-1} . The high strain rate test results matched the trends shown by the low strain rate data, following a similar profile and displaying a limited degree of strain rate dependence. The pressurised ball core results (Figure 5.12) appeared less cohesive than the pressureless ball core rubber (Figure 5.13). The pressurised ball core material shows a greater increase in stiffness with strain rate than is consistent with the low strain rate response. Furthermore, the 40 s^{-1} stress-strain response overlaps the low strain rate responses above 0.35 strain.

Figure 5.12 Mean stress-strain response of pressurised ball core rubber at all tested strain rates

Figure 5.13 Mean stress-strain response of pressureless ball core rubber at all tested strain rates

5.4.4 Dynamic Mechanical Analysis

Figure 5.14 and Figure 5.15 show the dynamic properties (storage modulus, G' , and loss modulus, G'') and damping properties ($\tan \delta$) of the pressurised and pressureless ball core rubbers respectively. Both materials exhibit a substantially larger storage modulus than loss modulus, resulting in a small loss tangent, indicating low energy losses. Consistent with rubber-like materials, the storage modulus decreases with increasing displacement amplitude, resulting in a larger loss tangent ($\tan \delta$). Additionally, the storage and loss moduli increase gradually below approximately 100 Hz, before

increasing at a faster rate. In turn, leading to much larger energy losses at higher frequencies (above ≈ 100 Hz).

Figure 5.14 DMA results for pressurised ball core rubber. A) storage (G') and loss modulus (G'') tested at different displacement amplitudes. B) $\tan \delta$ at different displacement amplitudes.

Figure 5.15 DMA results for pressureless ball core rubber. A) storage (G') and loss modulus (G'') tested at different displacement amplitudes. B) $\tan \delta$ at different displacement amplitudes.

5.5 Discussion

The aim of this chapter was to establish the tensile behaviour of tennis ball core rubber at strain magnitudes and strain rates present during impact. To some degree this has been achieved such that material behaviour at strain rates between 0.012 and 84 s^{-1} has been established, all with a minimum strain magnitude of 0.5 strain. Material behaviour at strain rates above 100 s^{-1} and up to 500 s^{-1} were desirable based on the results of physical strain measurement (4.4), however limitations with the test rig, whereby vibration and noise on impact between the drop tower and rig inhibited force measurement at the drop heights required to achieve the desired strain rates.

The tensile properties of both pressurised and pressureless ball core rubber have however been characterised across almost four logarithmic decades of strain rate from 0.012 – 84 s^{-1} . This has shown both rubber compounds have limited strain rate dependence between the maximum and minimum rates tested. The stiffness of both compounds is highly comparable to tensile data previously reported by Cordingley

(2002), Allen (2009) and Sissler (2012), whereby the stress at 0.1 strain is approximately 1 MPa and the stress at 0.5 strain is approximately 2.75 MPa, indicating a limited variation in tensile stiffness between multiple rubber compounds used in the manufacture of tennis ball cores. Furthermore, and in agreement with previous findings, the loading curve of the material was not highly non-linear at strains up to 0.5, nor was a large amount of hysteresis observed.

The relative lack of strain rate dependence brings into question the artificial stiffening of tensile data used in the creation of hyperelastic material models utilised by Cordingley (2002) and Sissler (2012). The stiffness of the hyperelastic model utilised by Sissler was approximately twice the stiffness of the quasi-static tensile data of the material. The limited increase in stiffness with increasing strain rate across the range tested in this investigation would suggest significantly less than a doubling in stiffness at strain rates in the region of 500 s^{-1} , if the current level of increased stiffness was extrapolated at the rates suggested from the tensile data collected. For this level of increase in stiffness, a transition would need to occur such that beyond a particular strain rate the rate of change in stiffness would need to increase significantly. Although plausible, it is perhaps the dynamic behaviour of the material that should be the focus of material modelling, rather than the rate dependence of the ball core rubber.

Although the design of the test rig would need to be altered to achieve the desired strain rates, the strain rates that were achieved produced tensile data in good agreement and alignment with that of the ElectroPuls. The capability of the rig surpassed the desired strain magnitude and produced tensile data at rates significantly faster than the ElectroPuls. The profile of the recorded data was in agreement with the low strain rate data and the increase in stiffness due to increased strain rate was also in keeping with quasi-static testing. Alongside the highly repeatable results produced, it highlights the validity of the approach in assessing the tensile properties of rubber-like materials, providing the desired strain rates don't exceed in the region of 100 s^{-1} .

The dynamic properties of pressurised and pressureless ball core rubber have also been assessed to determine the dynamic stiffness and damping properties of the material. Both materials exhibit typical rubber-like behaviour with both storage and loss moduli increasing gradually up to approximately 100 Hz before increasing more rapidly. Increasing the displacement amplitude also resulted in a reduction in storage modulus, known as the Payne effect (Luo *et al.* 2010). Although the pressurised core rubber had a higher storage modulus, similar $\tan \delta$ values were observed to the pressureless core rubber.

5.6 Conclusions

The results of this chapter presented the first reported assessment of ball core rubber properties across a range of strain rates from low to high strain rate ($> 10 \text{ s}^{-1}$). High strain rates were achieved through the development of a test rig used in combination with a drop tower. Additionally, the first reported assessment of the viscoelastic properties of ball core rubber has been conducted. The results of which enable the development of an FE model whereby experimentally determined multi-strain rate and viscoelastic material data can be utilised to model impact performance.

The stress-strain behaviour of ball core rubber has been determined across a range of strain rates from 0.012 s^{-1} to 84 s^{-1} at a magnitude of 0.5 strain. Although limitations with the test rig and drop tower combination did not allow for the highest of strain rates observed during impact testing, the results indicated that neither rubber compound is particularly strain rate dependent at the strain rates and strain magnitudes tested. It is hypothesised based on these findings, although not established, that the stiffness of the rubbers would not be subject to a dramatic increase in stiffness if the strain rate were increased from 84 s^{-1} to 500 s^{-1} . The results of FE strain analysis during impact have estimated however, between 47% (Sissler Model) and 51% (Cordingley Model) of tensile strain rate present during impact was above 100 s^{-1} (**Error! Reference source not found.**) for impacts at 90° and $52.5 \text{ m}\cdot\text{s}^{-1}$. Consequently, any impact due to lack of the highest strain rates observed are likely to be most pronounced at the most severe impact conditions.

The dynamic material properties have also been established using DMA between frequencies of 0.1 – 300 Hz. This enabled assessment of the dynamic stiffness and damping properties of each ball core rubber. Despite variation in the material compounds, both the tensile and dynamic properties of the two rubbers were very similar. This is perhaps surprising given the pressureless ball core is dependent solely on the rubber's material properties for its performance and does not have the benefit of an internally pressurised core.

Chapter 6. Finite Element Modelling of Tennis Ball Cores

6.1 Chapter Overview

Advanced viscoplasticity material models were employed to produce FE simulations of pressurised and pressureless ball cores during impact. The techniques used enabled the incorporation of multi-strain rate tensile data and viscoelastic material properties, producing a model based purely on experimentally determined material data. Simulations were compared to GOM surface strain analysis results (Chapter 4) and the effect of changing material properties on ball core performance was assessed.

6.2 Introduction

FE simulations provide a tool to assess the performance of ball cores and the effect of any changes to the material properties and/or the physical parameters (e.g. internal pressure). Simulations can provide fast and numerous predictions of the behaviour of ball cores with altered material properties and varying physical parameters. Although it is desirable to physically test altered cores in the laboratory, time, cost and availability constraints do not always allow.

FE simulations are however a trade-off between detail and computational efficiency, as such should be designed with the desired outcome in mind. The method of pressurisation, for example, can be achieved in a multitude of ways, some of which provide a more realistic representation of reality than others at the expense of computational efficiency (Hanson *et al.* 2015). Similarly, the aim of the material model is to capture as accurately as possible the behaviour of the material across multiple deformation modes, whilst remaining computationally efficient and without the need for excessive materials testing.

Modelling of tennis ball cores has seen significant attention (Cordingley 2002, Goodwill *et al.* 2005, Allen 2009, Sissler 2012), and can be broadly categorised into two approaches. Allen (2009) and Goodwill *et al.* (2005) utilised the Ogden constitutive model and Prony series, to capture the uniaxial and viscoelastic effects of the material. The Ogden material model was calibrated against tensile and compressive, whilst the Prony series coefficients were iteratively determined through comparison of the FE simulation to high-speed video footage and force trace data of ball core impacts. Cordingley (2002) and Sissler (2012) utilised the reduced polynomial constitutive model and applied a stiffness proportional damping factor to the entire model to account for

material damping properties (Abaqus β damping). The reduced polynomial model was calibrated against artificially stiffened tensile data and the damping value was determined iteratively by comparing against high-speed video footage.

Both approaches look predominantly to COR as a means of adjusting the chosen damping method, as COR is effectively a measure of energy loss in the system. As a result, it was necessary to physically test ball cores in the laboratory to compare the damped simulations against. Although comparison to impact testing was necessary to validate the model, it negates the potential benefit of FE simulations being used to assess potential new ball core materials if the approach taken to produce the model requires a physical prototype.

Due to the available test equipment, neither approach was able to directly measure the viscoelastic properties or strain rate dependence (however limited) of the material. Allen and Goodwill *et al.* utilised quasi-static tensile data while Cordingley and Sissler artificially stiffened quasi-static results to allow for rate dependent increases in stiffness. Results of Chapter 5 indicated limited rate dependence of ball core rubber for rates below 100 s^{-1} . Comparison of the material models used by Cordingley and Sissler (Figure 4.10) highlighted a wide range of stiffness can be implemented to produce comparable results by adjusting the stiffness and damping values accordingly, such that the individual contributions of strain rate dependency and damping properties are unknown.

Advances in material modelling and FE software packages has made the incorporation of elastic and viscoelastic properties across multiple modes more accessible. Models such as the Bergström-Boyce and Parallel Network model, are capable of predicting the time- and temperature-dependent behaviour of materials without the need for combining individual hyperelastic and viscoelastic component models. Such models have been successfully implemented to simulate the strain rate dependent behaviour of golf balls (Pugh 2011). The incorporation of measured viscoelastic material properties, through DMA testing, has also been successfully implemented in the modelling of soccer balls to determine accurate energy losses (Price 2005, Hanson 2014).

6.2.1 Aims & Objectives

Aim: to develop an FE model incorporating strain rate effects and viscoelastic properties to understand how changes to material properties and physical ball parameters effect ball performance.

Objectives:

- Create FE model based purely on measured material behaviour and validate against experimental data
- Assess the sensitivity of ball core performance to changes in material properties and physical parameters

6.3 FE Model Definition

The FE simulations described looked to build on the work of Cordingley and Sissler by incorporating the strain rate dependent and viscoelastic behaviour of ball core rubber, eradicating the need for artificial stiffening and damping factors. In doing so, much of the work presented by Cordingley and Sissler has been incorporated. The sphere representing the ball core was discretised into an icosahedron (Figure 6.1), a method shown to exhibit rotational symmetry and uniform impact characteristics (Cordingley 2002). The mesh also mirrored that of Cordingley and Sissler and comprised of two layers of six-node first order reduced integration wedge elements (C3D6R elements) resulting in 5,760 elements in total (Figure 6.1). The pressurised ball core had a mean outer diameter and wall thickness of 59.40 mm and 3.47 mm respectively. The mean mass of the pressurised core was 43.72 g, which equated to a material density of $1254 \text{ kg}\cdot\text{m}^{-3}$. The pressureless ball core had a mean outer dimension and wall thickness of 59.75 mm and 4.10 mm respectively. The mean mass of the pressureless core was 43.10 g, which equated to a density of $1078 \text{ kg}\cdot\text{m}^{-3}$. Six of each ball type were scrutinised, with dimensions measured using Vernier callipers and mass measured using an analytical balance (MT-20002B, Microyn Technologies Inc., Hunt Valley, MD).

Figure 6.1 Discretisation of the ball core and applied mesh

Pressurisation of the ball core was achieved by creating a fluid cavity inside surface of the ball core and a cavity reference point positioned at the centre of the cavity. Air was

used to pressurise the ball core was defined as a pneumatic fluid based on Abaqus documentation (Abaqus 2016b):

- Ideal gas molecular weight 0.0289 kg·mol⁻¹
- Absolute zero (θ^Z): - 293.15 K (such that the temperature of the simulation is equivalent to 20°C)
- Universal gas constant: 8.314 J·mol⁻¹
- Molar heat capacity:

$$c_p = a + b(\theta - \theta^Z) + c(\theta - \theta^Z)^2 + d(\theta - \theta^Z)^3 + \frac{e}{(\theta - \theta^Z)^2}$$

Where: $a = 28.11$, $b = 1.976 \times 10^{-3}$, $c = 4.802 \times 10^{-6}$, $d = - 1.966 \times 10^{-9}$, $e = 0.0$ J·mol⁻¹

- θ = temperature (K)

The fluid cavity utilised the uniform pressure method to define the pressure within the cavity using equations representing the thermodynamic properties of air, whereby at each point in time during the simulation the internal pressure was identical at each point of the inner surface of the cavity. Alternative methods, such as the coupled Eulerian Lagrangian (CEL), directly model the fluid, enabling the internal pressure of a cavity to vary temporally and spatially. Consequently, the CEL approach can predict the pressure wave generated on impact unlike the uniform pressure method. The CEL approach, in the context of soccer ball modelling, offered negligible improvements in model accuracy despite being significantly more computationally expensive (Hanson *et al.* 2015). As a result, the uniform pressure method is deemed suitable for ball core pressurisation.

The internal pressure of the core was increased gradually over the course of an analysis step to the desired pressure. Pressurised ball core models had an internal pressure of 83 kPa, with pressureless ball core models having an internal pressure of 7 kPa. The internal pressure of 83 kPa (12 psi) applied to the model was provided by the ball suppliers and consistent with previous works and the ITF technical department's description of ball manufacture (Sissler 83 kPa; Cordingley 82.4 kPa; Allen 85 kPa; ITF 82.7 kPa) (Cordingley 2002, Allen 2009, Sissler 2012, ITF 2014b). Although labelled pressureless, some internal pressure is applied to pressureless balls during manufacture to ensure the pressure inside the ball doesn't drop below atmospheric pressure on cooling or when transported. A maximum internal pressure of 7 kPa is defined by the ITF for a ball to be considered pressureless (ITF 2017b). All models were

run using Abaqus 2016 explicit solvers. The ball core was impacted normally against a rigid surface at velocities of 15 to 55 m·s⁻¹, at 5 m·s⁻¹ intervals.

6.3.1 Material Modelling

Previous examples of tennis ball modelling have not incorporated the strain-rate dependent behaviour of ball core rubber or incorporated experimentally determined viscoelastic material properties. Both of which have been investigated experimentally in Chapter 5.

Strain rate dependency of ball core rubber has either been omitted (Goodwill *et al.* 2005, Allen 2009), or represented through artificial stiffening of quasi-static test data with no experimental evidence of the appropriate stiffness (Cordingley 2002, Sissler 2012). Similarly, viscoelastic material properties have not been measured, instead incorporated either through model damping or manipulation of viscoelastic model coefficients. The primary reasons being unavailability of specialist test equipment and lack of required functionality of the FE software used at the time. Currently, it is not possible to calibrate a hyperelastic material model to multi-strain rate test data directly in Abaqus. To implement more advanced models would require the user to create complex material model scripts for use in Abaqus, as well a means of calibrating the model coefficients to test data. This body of work utilised MCalibration material model calibration software and PolyUMod material model implementation software (v4.6 Veryst Engineering, Needham, MA), enabling access to more advanced models than available in Abaqus as well as a means of calibrating the models to test data.

The use of MCalibration enables the use of viscoplasticity material models which are currently the most accurate and capable models for capturing the large-strain, time and temperature-dependent properties of rubberlike materials (Bergström 2015). Viscoplasticity models can be calibrated in MCalibration against multi-strain rate and viscoelastic material test data to create a single model used to predict material behaviour. Unlike in Abaqus where a separate viscoelastic definition is required alongside a hyperelastic material definition.

Of the viscoplasticity material models available, the Bergström-Boyce (BB) model was selected to capture the behaviour of the ball core rubber. The BB model has been showed to accurately predict the non-linear, time dependent, large strain properties of rubbers (Bergström and Boyce 1999, 2001, Qi and Boyce 2005), whilst being computationally efficient. Using MCalibration, the BB model can be calibrated against the multi-strain rate tensile and viscoelastic DMA data collected in Chapter 5, creating a

single model definition. This approach is deemed more simplistic than calibrating separate hyperelastic and viscoelastic models within Abaqus, with the benefit of the incorporation of multi-strain rate data, in addition to improved model capability and potential accuracy.

The BB model can also overcome potential limitations of the linear viscoelastic modelling approach of the in-built Abaqus representation of viscoelasticity (Bergström 2015). The BB model represents the response of the elastomer using two parallel networks A and B, such that the total stress is decomposed into an elastic component and a history dependent component. Network A represents the equilibrium response using the Eight-chain hyperelastic model. Network B represents the time-dependent response of the material using the Eight-chain model in series with a viscoelastic flow element (Figure 6.2).

Figure 6.2 Constitutive representation of the BB material model.

The flow element of the BB model is a generalisation of the linear viscoelastic model and can capture the dynamic behaviour of rubberlike materials. Experimentally, the storage and loss modulus of elastomers varies with strain amplitude and frequency, which can be captured by the BB model, unlike the linear viscoelastic model which assumes a linear response of storage and loss modulus with changes in strain amplitude or applied frequency.

The BB model has been selected for use in this body of work as it allows for the incorporation of multi-strain rate and viscoelastic test data, whilst offering a more advanced and capable modelling approach than available directly within Abaqus, which, through MCalibration can be simply calibrated and implemented. Advancing on previous tennis ball core modelling works by incorporating the strain-rate dependence and viscoelastic properties of ball core rubber with the FE simulations.

BB models for pressurised and pressureless ball core rubber were calibrated against two tensile loading profiles (0.012 s^{-1} and 6 s^{-1} stress-strain response from Chapter 5), to incorporate the strain rate dependent increase in stiffness, and DMA results collected within the linear range of the material, to incorporate the viscoelastic properties. The high strain rate material data collected in Chapter 5 was not included as the material exhibited relatively limited strain rate dependence. Furthermore, it was a case of striking a balance between adequate information describing the materials behaviour and convergence of the material model coefficients on a respectable solution. The resulting material model predictions against pressurised and pressureless ball core rubber are highlighted in Figure 6.3 and Figure 6.4 respectively, with the model coefficients described in Table 6.1.

Figure 6.3 BB material model calibration for pressurised ball core rubber. A) Tensile stress-strain prediction. B) Storage modulus prediction. C) Loss modulus prediction. D) Tangent delta.

Figure 6.4 BB material model calibration for pressureless ball core rubber. A) Tensile stress-strain prediction. B) Storage modulus prediction. C) Loss modulus prediction. D) Tangent delta.

Table 6.1 BB model coefficients implemented in FE simulations for pressurised and pressureless ball cores.

BB Model Coefficients	Units	Pressurised Model	Pressureless Model
mu	Stress (Pa)	1770892	1758398
lambdaL	-	1.634889	1.825451
kappa	Stress (Pa)	5E+08	5E+08
s	-	1.116314	0.737543
xi	-	0.153684	0.08
C	-	-1.94339	-2
tauBase	Stress (Pa)	539564.3	778043.5
m	-	1.100002	1.100001
tauCut	-	0.01	0.01

The resulting BB material models calibrated in MCalibration were able to incorporate multimodal (tensile data and shear DMA), multi-strain rate experimental data. What was evident however, compared to previous calibrations of a hyperelastic models against a single stress-strain profile was the closeness of the fit of the BB model is diminished. As the model is incorporating a range of data across different modes of deformation, an

exact match of the experimental data is difficult to obtain, particularly for dynamic data. The model prediction of storage and loss modulus is not an exact representation of the experimental data as the calibration software has to compromise between all of the inputted data when converging on the closest solution.

6.4 Experimental Ball Core Impacts (FE Validation)

Comparison of FE simulations against high-speed video footage of ball core impacts was utilised to assess and validate the accuracy of the pressurised and pressureless ball core models. As described in Chapter 4.3.4, a pneumatic cannon was used to fire ball cores normally against a rigid steel plate at 15 to 55 m·s⁻¹. In total 45 impacts per ball core were recorded, for which five of each core were used. Each ball core was subject to the same preconditioning procedure applied in Chapter 4. The ball cores were conditioned for 24 hours prior to use, at 20°C and 60% humidity, and subjected to nine pre-compressions by 2.54 cm through three perpendicular axes as defined by the ITF ball approval process (ITF 2017b).

The impacts were recorded using a Photron SA1.1 high-speed camera, positioned at 90° to the impact plate. The camera was recorded at 12,500 fps with a shutter speed of 1/12,000 s and was triggered by the ball passing through light gates positioned at the in front of the opening to the barrel. Resulting impact images were digitised in Matlab to determine COR, contact time and deformation across the range of velocity (Figure 6.6). Deformation was split into the tangential dimension and the normal dimension of the ball. The maximum tangential dimension of the ball was defined as the maximum dimension of the ball parallel to the impact plate during impact. The normal dimension was defined as the minimum perpendicular dimension of the ball during impact (Figure 6.5). These measures were used as a comparison against FE models to assess model validity.

Results of DIC surface strain measurement during impact (Chapter 4) were also used as a means of validating FE simulations. FE estimations of strain, at regular time intervals corresponding to the recorded impact images, were compared against the measured values determined previously.

Figure 6.5 Schematic representation detailing normal dimension and tangential dimension.

Figure 6.6 Experimental ball impact results for pressurised and pressureless ball cores showing (A) COR response, (B) contact time, (C) normal dimension and (D) tangential dimension.

6.5 Pressurised Ball Core FE Model: Results

Figure 6.7 Pressurised ball core FE simulation results compared to experimental results, showing (A) COR response, (B) contact time, (C) normal dimension and (D) tangential dimension.

The FE simulations of the pressurised ball core compare favourably against experimental impacts of pressurised ball cores across the range of velocities modelled (Figure 6.7). COR and the tangential dimension of the core during impact are closely matched by the simulations. Simulated contact time also compares well with experimentally measured values particularly at velocities up to and including $40 \text{ m} \cdot \text{s}^{-1}$. Simulations slightly underestimated contact time and diverged from experimental values with increasing impact velocity. The simulated minimum normal dimension of the ball core during impact was less in keeping with experimentally measured values, overestimating the deformation (resulting in a smaller dimension) of the ball by as much as 5 mm. The FE simulations showed increased deformation across the mid-range velocities from 25 to $40 \text{ m} \cdot \text{s}^{-1}$.

Figure 6.8 to Figure 6.10 compared the FE simulations against the GOM strain analysis results collected in Chapter 4 both visually and as a distribution of strain. The comparison at $20 \text{ m} \cdot \text{s}^{-1}$ shows the simulation compared favourably with the GOM strain measurements as well as replicating well the deformation profile of the ball during impact

(Figure 6.8). Comparisons at $30 \text{ m}\cdot\text{s}^{-1}$ and $40 \text{ m}\cdot\text{s}^{-1}$ showed greater differences between the model and experimental data (Figure 6.9 & Figure 6.10). Between initial contact and maximum deformation (0 – 1.92 ms) the FE model was able to relatively closely match the strain and deformation profile of the GOM strain analysis. Differences were apparent as the ball recovered between max deformation and end of contact, with simulations over predicted strain with greater differences in shape profile observed.

Figure 6.8 Comparison of pressurised ball core FE simulation and GOM strain analysis for a 20 m·s⁻¹ impact. Surface strain map and distribution.

Figure 6.9 Comparison of pressurised ball core FE simulation and GOM strain analysis for a 30 m·s⁻¹ impact. Surface strain map and distribution.

Figure 6.10 Comparison of pressurised ball core FE simulation and GOM strain analysis for a 40 m·s⁻¹ impact. Surface strain map and distribution.

6.6 Pressureless Ball Core Model: Results

Figure 6.11 Pressureless ball core FE simulation results compared to experimental results, showing (A) COR response, (B) contact time, (C) normal dimension and (D) tangential dimension.

FE simulations of pressureless ball cores were much less accurate than their pressurised counterparts when compared to experimental data and GOM strain analysis results. Although contact time and the maximum tangential dimension of the ball during impact were highly comparable, the COR and minimum normal dimension were significantly underestimated (Figure 6.11). The reduced COR values predicted by FE simulations implied the viscoelastic properties of the material aren't being replicated adequately. As was the case with the pressurised core, the FE simulations of the pressureless core overpredict deformation perpendicular to the impact plate.

Compared to GOM strain analysis, the FE simulations provide an accurate estimation of strain and deformation from initial contact to 2 ms for impacts at $20 \text{ m} \cdot \text{s}^{-1}$ and 1.33 ms for impacts at 30 and $40 \text{ m} \cdot \text{s}^{-1}$ (Figure 6.12, Figure 6.13, Figure 6.14). The latter phases of impact predicted by simulations was much less in keeping with the GOM analysis, with the deformation profile of the pressureless core differing considerably after 3.33 ms for a $30 \text{ m} \cdot \text{s}^{-1}$ impact and 2.5 for a $40 \text{ m} \cdot \text{s}^{-1}$.

Figure 6.12 Comparison of pressureless ball core FE simulation and GOM strain analysis for a 20 m·s⁻¹ impact.

Figure 6.13 Comparison of pressureless ball core FE simulation and GOM strain analysis for a 30 m·s⁻¹ impact.

Pressureless Ball Core 40 m·s⁻¹

Figure 6.14 Comparison of pressureless ball core FE simulation and GOM strain analysis for a 40 m·s⁻¹ impact.

6.7 Sensitivity Analysis

To assess the importance of isolated material properties on the performance of ball cores and gauge the degree to which parameters can vary before performance is adversely affected, a sensitivity analysis was performed on both the pressurised and pressureless ball core models. The pressureless model was included, despite lacking accuracy compared to experimental impact data, to assess what aspect of the experimental data could be inhibiting the accuracy of simulations.

Isolated parameters, namely; density, internal pressure, tensile stiffness, storage modulus and loss modulus, were systematically varied and simulated to judge the effects on performance. Density and internal pressure were manually altered in the FE software. Cordingley (2002) and Sissler (2012) were able to vary a single material model coefficient to vary stiffness. As the BB model is more complex and encompasses more than just a single tensile loading curve, the approach of altering material model coefficients was not deemed suitable. As a result, the respective experimental data was manipulated and a new material model was calibrated against the modified experimental data in MCalibration. A new BB material model was calibrated for changes to tensile stiffness, storage modulus and loss modulus, the results of which are displayed in Table 6.2 and Table 6.3 for the pressurised and pressureless models respectively. Each parameter was varied by $\pm 20\%$. All other parameters remained unchanged from the original data used to produce the ball core model. The results of sensitivity analysis were compared against the original ball core model to assess changes in performance (COR, contact time, normal dimension and tangential dimension).

Table 6.2 Pressurised core BB material model coefficients used to perform sensitivity analysis.

Model Coefficients	Stiffness -20%	Stiffness +20%	Storage Modulus -20%	Storage Modulus +20%	Loss Modulus -20%	Loss Modulus +20%
mu	1343954	2103152	1671188	1761535	1734534	1741706
lambdaL	1.474847	1.582039	1.437202	1.625535	1.554541	1.568996
kappa	5E+08	5E+08	5E+08	5E+08	5E+08	5E+08
s	1.88879	0.852543	1.09894	1.582085	1.173577	1.224226
xi	0.106239	0.146528	0.139811	0.050003	0.102126	0.100022
C	-1.99999	-1.72937	-1.65501	-1.82785	-1.59915	-1.62152
tauBase	695587.2	487056.5	500000.4	764353.6	560053	579779.1
m	1.34956	1.100018	1.1	1.599746	1.100008	1.100044
tauCut	0.01	0.01	0.01	0.01	0.01	0.01

Table 6.3 Pressureless core BB material model coefficients used to perform sensitivity analysis.

Model Coefficients	Stiffness -20%	Stiffness +20%	Storage Modulus -20%	Storage Modulus +20%	Loss Modulus -20%	Loss Modulus +20%
mu	1398442	2117968	1757361	1720919	1790529	1864459
lambdaL	2.332227	1.816208	1.640097	2.932469	8.681305	2.928118
kappa	5E+08	5E+08	5E+08	5E+08	5E+08	5E+08
s	1.128545	0.430814	0.410541	0.932186	0.566902	0.6242
xi	0.089134	0.05	0.05	0.07	0.05	0.050002
C	-1.99796	-1.48062	-2	-1.99999	-1.39741	-2
tauBase	962489.4	537584.7	415054.6	500000.9	612174.9	679927.4
m	1.100004	1.1	1.1	3.043748	1.100004	1.100028
tauCut	0.01	0.01	0.01	0.01	0.01	0.01

6.7.1 Pressurised Ball Core Sensitivity Analysis: Results

Changing the density of the pressurised ball core material by $\pm 20\%$ had an effect on COR, contact time and minimum normal dimension (Figure 6.15). Reducing density lead to increased COR and reduced contact time. Additionally, a reduction in density led to a reduction in normal deformation, resulting in increased minimum normal dimension. Increasing the density produced the opposite effect on COR, contact time and normal dimension, whilst changing density had minimal impact on the maximum tangential dimension of the ball during impact.

A 20% change in internal pressure produced similar findings to changes in density, with COR, contact time and normal dimension affected (Figure 6.16). Increasing the internal pressure by 20% also produced a greater response than reducing it. COR increased with internal pressure across the range of impact velocities simulated. Increasing internal pressure also reduced the degree of normal deformation resulting in an increase in the minimum normal dimension during impact.

Altering the stiffness of the tensile data had a limited impact on contact time, normal dimension and tangential dimension (Figure 6.17). Differences in COR were observed; however, these differences were more pronounced at lower impact velocities (below $30 \text{ m}\cdot\text{s}^{-1}$), unlike when changing density and internal pressure where the effect was sustained across the range of impact velocities. Increasing stiffness increased COR and vice versa, albeit reducing stiffness exhibited a greater reduction.

The sensitivity of the model to changes in storage modulus were limited to COR (Figure 6.18). The model with increased storage modulus significantly reduced the COR across all impact velocities. This result was unsuspected since increasing the storage modulus whilst maintaining the same loss modulus should result in a reduction in energy loss, of which COR is effectively a measure. It would appear the material model for increased storage modulus has not accurately captured the altered viscoelastic properties. Furthermore, changes made to the loss modulus showed no impact on COR, contact time, normal dimension and tangential dimension when compared to the original pressurised model simulation (Figure 6.19). As a result, the model is either insensitive to a $\pm 20\%$ change in storage and loss modulus or the material model is not precise enough to replicate subtle changes in dynamic material behaviour.

Figure 6.15 Sensitivity of the pressurised ball core FE model to a $\pm 20\%$ change in density, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.16 Sensitivity of the pressurised ball core FE model to a $\pm 20\%$ change in internal pressure, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.17 Sensitivity of the pressurised ball core FE model to a $\pm 20\%$ change in tensile stiffness, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.18 Sensitivity of the pressurised ball core FE model to a $\pm 20\%$ change in storage modulus, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.19 Sensitivity of the pressurised ball core FE model to a $\pm 20\%$ change in loss modulus, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

6.7.2 Pressureless Ball Core Sensitivity Analysis: Results

As with the pressurised model, changes to density effected COR, contact time and normal dimension, with minimal impact on tangential dimension (Figure 6.20). Decreasing density showed a significant increase in COR across all impact velocities and vice versa. The effect of density on contact time was more pronounced at the extremities of tested impact velocities, with similar values to the original model exhibited from $30 \text{ m}\cdot\text{s}^{-1}$ to $45 \text{ m}\cdot\text{s}^{-1}$. A reduction in density also increased the minimum normal dimension, implying reduced normal deformation. The effect of density on the normal dimension was only present at velocities up to $35 \text{ m}\cdot\text{s}^{-1}$.

The sensitivity of the pressureless ball core to changes in internal pressure were limited (Figure 6.21), probably a result of the starting point being very low, as such the real terms change is small despite a notable change in percentage terms ($\pm 20\%$). A minimal change was observed in COR between $15 \text{ m}\cdot\text{s}^{-1}$ and $25 \text{ m}\cdot\text{s}^{-1}$ however all remaining results showed no significant difference to the original pressureless ball core model.

The COR response of the pressureless core model showed the greatest sensitivity to changes in tensile stiffness (Figure 6.22). Increased stiffness exhibited a significant increase in COR, particularly at velocities below $35 \text{ m}\cdot\text{s}^{-1}$, producing a model more in keeping with the experimental data than the original pressureless model. Changes to tensile stiffness had minimal impact on contact time and no impact on the deformation measures.

The results of changing the storage modulus of the pressureless ball core material were inconsistent with expectations (Figure 6.23), as was the case with the pressurised core model response to changes in storage modulus. For example, both increasing and decreasing storage modulus resulted in a decrease in COR and increase in contact time compared to the original model. Increasing storage modulus was expected to increase COR and vice versa, since the ratio between the storage modulus and loss modulus results in variation of the loss tangent ($\tan \delta$). The model with reduced storage modulus is in keeping with expectation; resulting in reduced COR, increased contact time and decreased normal dimension. As was the case with the pressurised model equivalent, the results of the increased storage modulus model were unexpected.

Changes to loss modulus were more in keeping with expectations than changing storage modulus, with reduced loss modulus resulting in reduced energy loss and increased COR (Figure 6.24). Increasing loss modulus showed a slight increase in contact time,

whilst neither increasing or decreasing loss modulus was deemed to affect the normal or tangential dimension.

Figure 6.20 Sensitivity of the pressureless ball core FE model to a $\pm 20\%$ change in density, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.21 Sensitivity of the pressureless ball core FE model to a $\pm 20\%$ change in internal pressure, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.22 Sensitivity of the pressureless ball core FE model to a $\pm 20\%$ change in tensile stiffness, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.23 Sensitivity of the pressureless ball core FE model to a $\pm 20\%$ change in storage modulus, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

Figure 6.24 Sensitivity of the pressureless ball core FE model to a $\pm 20\%$ change in loss modulus, effect on (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

6.8 Discussion

This chapter has highlighted it is possible to produce an accurate FE model of pressurised tennis ball cores, without the need for artificial stiffening of tensile data or artificial deduced damping. The model incorporated strain-rate dependence and viscoelastic properties through calibration against tensile stress-strain profiles at two strain rates (0.012 s^{-1} and 6 s^{-1}) and DMA data collected in the shear deformation mode. The approach was made significantly simpler through utilisation of the BB viscoplasticity material model, which enabled the incorporation of multimodal, multi-strain rate data into a single material model for implementation in Abaqus, negating the need for individual hyperelastic and viscoelastic components to the material model.

Unfortunately, the same modelling approach did not produce an accurate representation of the pressureless ball core during impact, particularly in the recovery phase of impact from maximum deformation to separation from the impact plate, whereby the shape profile of the ball core was not closely matched. The FE estimation of COR was particularly low, indicating the viscoelastic properties have not been adequately represented by the material model. Furthermore, the overestimation of deformation perpendicular to the impact plate, resulting in decreased normal dimension compared to experimental results, was common for pressurised and pressureless ball core models and is an area of the simulation where accuracy can be improved. Increased deformation coincided with slightly elevated surface strain when compared to GOM surface strain measurements (Pressurised: Figure 6.8 - 6.10; Pressureless: Figure 6.12 – 6.14).

When assessing the predictions of the material model against the experimental data used to calibrate the model (Figure 6.3 – 6.4); the ability of the BB model for the pressureless core to replicate the loss modulus of the material at frequencies above 1 Hz was considerably poorer than the pressurised equivalent, albeit neither model precisely matched the storage or loss modulus across the frequency range. It is hypothesised that the representation of the dynamic properties of the pressureless material contributed significantly to the inaccuracies of the FE simulations, in particular the COR estimation but also the excessive deformation resulting in underestimation of the minimum normal dimension during impact.

To further improve model accuracy the investigating of more complex viscoplasticity material models, such as the M8 and parallel network model, all available within the MCalibration software. More complex models enable a customisable model framework from which an array of hyperelastic and viscoelastic model components can be

implemented within a chosen number of parallel networks. More complex models would however be more difficult to accurately calibrate and likely be much less computationally efficient than the BB model.

Sensitivity analysis of both pressurised and pressureless ball core models highlighted the effect of varying material properties on impact performance. The maximum tangential dimension of the ball core during impact (how much the ball is bulging) showed little to no response to changes in density, internal pressure, stiffness, storage modulus or loss modulus.

Material density was shown to effect COR, contact time and normal dimension to a greater extent than changes to internal pressure or stiffness. Variation in internal pressure produced a similar response to density, but to a lesser degree, particularly in the case of the pressureless core model. The sensitivity of the FE models to material stiffness was limited to COR, where a reduction in stiffness resulted in a reduction in COR.

The results of the sensitivity analysis imply a relatively large window exists ($\pm 20\%$) for the stiffness of a given material to perform adequately as a tennis ball core, providing the damping properties are similar to that of current materials. Furthermore, the density of any potential alternative material and the internal pressure within the core could be used to tune the alternative core to more closely match the desired impact performance.

The effect of changing either the storage or loss modulus proved inconclusive and magnified the need to improve the calibration of the material model against the dynamic experimental data. The results of the FE simulations and sensitivity analysis highlight the difficulty in implementing dynamic data into an all-encompassing viscoplasticity material model. The inclusion multiple tensile stress-strain data with dynamic data results in a compromise of the best overall fit when calibrating the material model. When successful however, the benefits are significant as the need to iteratively and artificially 'correct' a model against experimental data is diminished and the real-world applicability of the model increased.

6.9 Conclusions

The work presented in this chapter has produced novel FE simulations of tennis ball cores through use of viscoplasticity material modelling (BB model), enabling the incorporation of strain rate dependent and viscoelastic material properties. The simulations are the first example of a ball core model incorporating multi-strain rate and dynamic experimental data, eradicating the need for tuning of model parameters to

match experimental data of ball core impacts. Consequently, the modelling process undertaken is suitable for the assessment of potential TPE ball cores as the model does not require tuning against prototype ball impact results.

Utilisation of the BB viscoplasticity model, calibrated against two tensile stress-strain profiles and a single DMA frequency sweep produced a sufficiently accurate representation of the pressurised ball core during impact. Conversely, the same technique proved less accurate when modelling pressureless ball cores. The pressureless ball core model equivalent was not deemed sufficiently accurate, due to inadequate representation of COR and deformation perpendicular to the impact plate. In general, the modelling technique applied overestimated the deformation of the ball core normal to the impact surface (squash dimension), such that simulations estimated increased deformation, further highlighted overestimation of strain when compared against measured strain during impact.

The BB model eradicated the need to artificially tune FE models against high-speed video footage (and/or force trace data) of ball impacts. However, the task of accurately capturing the materials tensile and dynamic behaviour within a single model proved challenging, since the material model compromises between all of the given experimental inputs. The FE models, in particular the pressureless model, may be improved through use of more complex viscoplasticity material models such as the parallel network model. The sensitivity of FE simulations to changes in storage and loss modulus were inconclusive, with either minimal difference or unexpected differences displayed.

Sensitivity analysis of the FE models to changes in internal pressure, material density and stiffness indicated the relationship between the parameters could be varied to manipulate the performance of a given material to more closely match the current ball core. For example, a stiffer material than that of ball core rubber could be manipulated to perform in a more similar manner through reducing the internal pressure or increasing the material density.

Chapter 7. Alternative TPE Materials for Tennis Ball Cores

7.1 Chapter Overview

Categories of TPE showing similar properties to natural rubber are identified, from which specific grades were sourced. The TPE samples were characterised following the process formed in Chapter 6, establishing the multi-strain rate and viscoelastic material properties. The properties of the TPEs were then directly compared to ball core materials.

7.2 Introduction

The term 'rubber' is associated with long-chain polymer molecules with a glass transition temperature below room temperature. Additionally, the term 'elastomer' is used to describe a cross-linked (thermoset) rubber that is elastic in nature. Elastomers have a high degree of flexibility and mobility which allows for high deformability. When subjected to external stresses the long polymer chains alter their configuration rapidly due to high mobility. When the stress is removed the materials original dimensions can be restored with no or limited set (Drobny 2007). The macromolecules within traditional thermoset elastomers are chemically bonded to one another, through the process of vulcanisation, forming a giant three dimensional molecule of high molecular weight (Abraham and McMahan 2004). A plastic material is capable of being moulded, with thermoplastics mouldable through the application of heat. The vulcanisation process results in a loss of thermoplasticity due to the presence of cross-links, hence the material cannot flow when exposed to heightened temperatures.

A thermoplastic elastomer (TPE), as the name suggests, is both thermoplastic and elastic in nature, combining the service properties of elastomers with the processing properties of thermoplastics. For a specified service temperature range TPEs are elastomeric, whilst at elevated temperature the material can be moulded and remoulded, as is the case with thermoplastic materials. This is possible as the intermolecular bonds present in TPEs are thermo-reversible, unlike in thermoset materials whereby the polymer chains are chemically cross-linked and covalently bonded together.

The majority of TPEs are phase-separated systems, possessing a biphasic morphological structure, with the exception of a handful of single-phase materials, such as melt processible rubber (MPR, e.g. Alcryn). Generally, TPEs consist of a crystalline and/or hard phase and an amorphous soft phase. The hard phase is usually solid at ambient temperature and gives the system strength, similar to the cross-links present in

vulcanised thermoset materials. The soft phase is an elastomer providing elasticity and flexibility to the system. The hard and soft phases must be thermodynamically incompatible with each other at the desired service temperature to prevent interpenetration of the hard and soft phases (Costa *et al.* 2008).

TPEs are categorised based on the chemical composition of the polymers the material contains according to the standard BS EN ISO 18064:2014 (British Standards Institution 2014). The prefix 'TP' designates the material is a thermoplastic elastomer, followed by a letter to represent the TPE category as highlighted in Table 7.1.

Table 7.1 BS EN ISO 18064:2014 TPE category definitions.

TPE Category		Criteria according to BS EN ISO 18064:2014
TPA	Thermoplastic polyamide	Block copolymer of alternating hard and soft segments. Amide bonds in the hard blocks and ether and/or ester bonds in the soft blocks.
TPC	Thermoplastic copolyester	Block copolymer of alternating hard and soft segments containing in the main ether and/or ester bonds.
TPO	Thermoplastic polyolefin	Blend of a polyolefin with a conventional rubber containing little or no cross-links.
TPS	Styrene block copolymer	Copolymer (at least triblock) of styrene and a specific diene. Two polystyrene 'hard' end blocks with 'soft' internal block consisting of a polydiene or hydrogenated polydiene.
TPU	Thermoplastic polyurethane	Block copolymer of alternating hard and soft segments. Urethane bonds in the hard blocks and ether, ester and/or carbonate bonds in the soft blocks.
TPV	Thermoplastic vulcanizate	Blend of a thermoplastic material and a conventional rubber cross-linked by dynamic vulcanisation.
TPZ	Unclassified	TPE consisting of a blend or structure not described in any of the above.

The rubber used in the manufacture of tennis balls is thermoset, primarily natural rubber, although the exact compound is the proprietary formulation of the manufacturer. A number of procedures and additives are required before a finished product can be obtained. Firstly, the raw rubber is masticated to reduce the viscosity of the rubber to a desired value. The rubber is then be compounded with fillers, plasticisers and accelerators, as necessary, to obtain the desired material properties and processing characteristics (ITF 2014b). Once moulded, the material must also be cured or vulcanised, whereby the chemical cross-links are formed within the material, rendering excess flash as waste, as the material cannot be remoulded. As a result, TPEs offer a number of advantages over traditional thermoset elastomers.

TPEs offer simpler material processing as the final part may be produced in fewer processes using traditional thermoplastic processing methods (e.g. injection moulding). The material can often be obtained fully formulated in pellet or granular form, with no masticating and little or no compounding required. Fabrication times are also reduced as the need for curing time is eliminated, resulting in mould times in the order of seconds rather than minutes. These advantages lead to shorter production times, more efficient processes and the possibility of reduced energy consumption. The traditional plastic material processes can also offer improved quality control and tolerances compared to moulding thermoset elastomer. TPE resins exhibit greater reproducibility and consistency of properties, as a result, quality control cost can be reduced. Excess and scrap material can also be used as regrind and remoulded (Drobny 2007).

TPEs are not however without their disadvantages. The service temperature of TPEs must be well below the melting point of the material. TPEs have a tendency to yield and flow under high stresses, particularly at elevated temperatures (Gent 2001). There are also a limited number of TPEs offering low hardness, where the hardness of the material has a Shore A hardness less than 50. Furthermore, TPEs typically require drying, by exposing the material to elevated temperature and low humidity to remove moisture prior to fabrication (Drobny 2007).

7.2.1 Aims & Objectives

Aim: to identify alternative TPE materials for use in tennis ball cores and characterise their behaviour.

Objectives:

- Identify potential TPE materials with properties close to that of tennis ball core rubber.
- Characterise the low strain rate tensile behaviour using commercially available testing equipment.
- Characterise the high strain rate tensile behaviour using the test rig developed in Chapter 5.
- Utilise DMA to assess the viscoelastic properties of alternative TPE materials.
- Compare the properties of alternative TPE materials to results from tennis ball core rubber materials.

7.3 Material Selection

Initially the generic properties of TPEs were assessed using CES EduPack materials selection software (Granta Design Ltd., Cambridge, U.K.). This enabled the comparison of TPE properties to be compared to the generic properties of filled natural rubber, providing an indication into the types of TPE worthy of consideration for testing.

Figure 7.1 highlights the shear and Young's modulus of natural rubber and TPE materials, displaying TPE materials with overlapping properties to natural rubber. Similarly, TPEs have displayed a similar loss coefficient ($\tan \delta$) and are of comparable density to natural rubber (Figure 7.2), although the range in loss coefficient for natural rubber is larger than the value measured during the characterisation of ball core rubber (Chapter 5). The graphs indicate TPEs exist with mechanical properties similar to that of ball core rubber. Variation in density would require the thickness of an alternative ball to be altered to maintain a constant mass, as is the case with pressureless and pressurised ball cores. The pressureless ball core material exhibited increased wall thickness compared to the pressurised ball core, to account for the reduced density of the compound. In addition to mechanical properties, material selection software highlighted potential improvements in gas barrier properties were TPEs to replace natural rubber, with some TPEs displaying less than half the permeability to oxygen as natural rubber (Figure 7.3). A potential issue being the cost of TPEs compared to natural rubber is also highlighted as the feasibility of using a TPE alternative would need to be considered should any provide a viable alternative. Figure 7.3 displayed a maximum cost for natural rubber of £2 per kg, whereas some TPEs cost more than £6 per kg.

Figure 7.1 Shear and Young's modulus of natural rubber (blue) and TPEs (red) (CES EduPack).

Figure 7.2 Density and tan δ of natural rubber (blue) and TPEs (red) (CES EduPack).

Figure 7.3 Price and permeability to oxygen of natural rubber (blue) and TPEs (red) (CES EduPack).

The highlighted material selection charts, combined with discussions with material suppliers, resulted in the acquisition of the TPE materials highlighted in Table 7.2. The application of the material was discussed with suppliers and suggestions as to specific material grades were made. Different types of TPE were identified that were, in some part, comparable to generic natural rubber, using material selection charts comparing the different material types. The selection charts (Figure 7.1 - Figure 7.3) indicated TPU, TPO, TPV and MPR were similar in some respect to natural rubber. Specific material grades of each type were then sought from materials suppliers. The application of tennis ball core material was discussed, and specific grades recommended based on the

knowledge and experience of the suppliers, culminating in the acquisition of the TPE grades highlighted in Table 7.2.

Table 7.2 TPE Materials obtained for investigation.

Supplier	Material Trade Name	TPE Type	Grade	Density (kg/m ³)	Shore Hardness (A/D)
A. Schulman	Alcryn	TPZ, MPR	UT2250	1060	47 (A)
			UT2265	1080	62 (A)
Covestro	Desmopan	TPU	DP 9370AU	1060	70 (A)
			DP 85085A DPS 055	1130	85 (A)
DuPont	Hytrel	TPC	3078	1070	30 (D)
			G3548L	1150	35 (D)
			4068	1110	40 (D)
ExxonMobile	Santoprene	TPV	101-55	970	59 (A)
			101-64	970	69 (A)

Alcryn MPR: is a melt processible rubber, based on partially cross-linked, chlorinated olefin interpolymer alloy. Alcryn is marketed as a true rubber capable of being processed on thermoplastic processing equipment. Alcryn differs from the vast majority of TPEs as it is claimed to be a single-phase system. It does not require pre-drying or compounding and has found use in many applications served by vulcanised rubbers such as seals, gaskets and tubing.

Desmopan TPU: The DP 85085 grade is based on an aliphatic isocyanate injection moulding grade, used for automotive interior parts. The DP 9370 grade is an ether-based injection moulding grade, used in seals, membranes and outsoles of athletic footwear.

Hytrel TPC: is a block copolymer of polyester. Semi-crystalline hard phase (usually PBT polybutylene terephthalate) with a polyether amorphous soft phase. It is used in cable insulation, ski boots, tubing and mobile phone housing.

Santoprene TPV: is a dynamically vulcanised alloy consisting mostly of fully cured EPDM rubber particles within a polypropylene matrix. It differs fundamentally from block copolymer TPEs as the thermoset rubber is dispersed within the polymer matrix rather than chemically incorporated into the polymer chains. Soft, thermoplastic vulcanizate used in the automotive and consumer electronics industry as gaskets, seals and tubing.

7.4 TPU Fabrication

With the exception of Desmopan TPU, all suppliers shipped fabricated sheets of material direct, the default thickness for which was 2 mm, consistent across all the suppliers. It was not possible to obtain a desired thickness, such as one closer representing ball core thickness. Desmopan TPU differed in that the supplier sent granulated material rather than fabricated sheets, hence the need to mould the TPU into a useable form. To maintain consistency between TPE samples, a thickness of 2 mm was chosen when moulding the TPU into sheet form. Prior to fabrication the granules were dried according to the manufacturer's instructions at 60°C for 3 hours using an environmental chamber (Alpha 190H, Design Environmental Ltd.) (Bayer MaterialScience AG 2008). This was necessary to reduce the moisture content within the material and reduce the likelihood of surface imperfections and hydrolytic degradation.

The granules were placed in a 2 mm thick steel picture frame mould and formed using a hydraulic press (LabTech Engineering Company Ltd.). The material was pressed at a temperature of 190°C for 12 minutes, followed by 3 minutes of cooling. Both grades of the material were subject to these conditions, forming 2 mm thick rectangular sheets of the material as shown in Figure 7.4.

Figure 7.4 TPU fabrication showing pre-moulded granules (A) and fabricated material (B).

7.5 Material Characterisation

7.5.1 Tensile Testing Methodology

Both the low strain rate and high strain rate tensile testing procedures followed the same procedure used for the characterisation of ball core rubber defined in Chapter 5.3. The same ElectroPuls test speeds and drop heights were used to replicate the test conditions used to characterise ball core rubber. ISO 37 type 1 tensile samples were cut directly from the acquired sheets of TPE material. Five repeats at each test speed and drop height were conducted.

7.5.2 DMA Methodology

DMA testing followed the same procedure described in Chapter 5.3.3 for the testing of ball core rubber. The samples were tested in shear and the limit of the linear range was determined by performing a displacement sweep on each TPE material and assessing the force and modulus response. The displacements amplitudes employed for each TPE material are defined in Table 7.3. The smallest displacement amplitude for each material represents the test amplitude performed within the linear range of the material.

Table 7.3 DMA displacement amplitudes for TPE materials.

TPE Material	Material Grade	Displacement 1 (µm)	Displacement 2 (µm)	Displacement 3 (µm)
Alcryn MPR	2250	10	100	120
	2265	9	20	50
Desmopan TPU	9370	9	20	50
	85085	3	20	50
Hytrel TPC	3078	5	20	60
	3548	3	20	60
	4068	3	20	50
Santoprene TPV	101-55	8	50	100
	101-64	4	50	100

7.5.3 Properties: Melt Processible Rubber (Alcryn)

Figure 7.5 Mean low and high strain rate tensile results MPR grades, (A) Alcryn 2250 and (B) Alcryn 2265.

Both grades of MPR displayed strain rate dependent behaviour, particularly evident above 0.15 strain. The 2265 grade (Figure 7.5B) had a more uniform increase in stiffness than the more compliant 2250 grade. The response of Alcryn 2250 at the slowest strain rate tested (0.012 s^{-1}) showed significantly lower stresses for strains above 0.3 than the remaining low strain rates tested ($\leq 6 \text{ s}^{-1}$). The stiffness of the 2265 grade is in the region of twice the stiffness of the 2250 grade, although the response of Alcryn 2250 is more non-linear.

High strain rate tensile testing of the 2265 grade was in keeping with the profile of the low strain rate data, showing increased stiffness with strain rate. High strain rate testing of Alcryn 2250 does not follow the same loading response as low strain rate testing, highlighted by significantly stiffer behaviour up to 0.3 strain before a drop off in stress occurred. The slowest of the high strain rate tests (36 s^{-1}) follows the loading profile of low strain rate data more closely, however stiffness is similar to that of the lowest strain rate tested (0.012 s^{-1}), highlighting inconsistencies in high strain rate results.

Figure 7.6 Dynamic properties of MPR at different displacement amplitudes. Storage modulus (G'), loss modulus (G'') and $\tan \delta$ response of Alcryn 2250 (A, C) and Alcryn 2265 (B, D).

Figure 7.6 illustrates the dynamic properties of Alcryn MPR, with neither grade showing a notable change in response with increased displacement amplitude. Both grades follow a similar profile for storage modulus, loss modulus and $\tan \delta$, with all increasing steadily up to a frequency of 100 Hz. The storage and loss modulus for the 2265 grade are more double that of the 2250 grade, with an increased $\tan \delta$ also displayed.

7.5.4 Properties: Thermoplastic Polyurethane (Desmopan)

Figure 7.7 Mean low and high strain rate tensile results TPU grades, (A) Desmopan 9370 and (B) Desmopan 85085.

DP85085 is significantly stiffer than DP9370, indicated by stresses in the region of 4 MPa at 0.5 strain compared to 2.5 MPa (Figure 7.7). The low strain rate tensile response of both TPU grades exhibited strain rate dependent behaviour, apparent above strain

magnitudes of 0.1 and 0.2 strain for DP9370 and DP85085 respectively. Stiffness increased uniformly with increasing low strain rates. As experienced with MPR, the high strain results are more varied. The high strain rate response for both materials initially appeared plausible and in keeping with the corresponding low strain rate response, but only up to 0.4 strain. Above which, the rate of increase in stress declines such that the response crosses over the low strain rate data. Below 0.4 strain, the loading response is similar to that of low strain rate testing, with slight increases in stiffness observed with increasing strain rate.

Figure 7.8 Dynamic properties of TPU at different displacement amplitudes. Storage modulus (G'), loss modulus (G'') and $\tan \delta$ response of Desmopan 9370 (A, C) and Desmopan 85085 (B, D).

The storage and loss modulus of Desmopan TPU increased gradually with increasing frequency of oscillation (Figure 7.8). The storage modulus of DP 85085 reduced with increasing displacement amplitude, a trend not displayed by DP 9370. The storage modulus was also more than double for DP 85085, in excess of 10 MPa. The $\tan \delta$ response of the two grades differed in profile, with DP 9370 displaying a gradual increase in $\tan \delta$ up to 100 Hz, whereas DP 85085 displayed a more non-linear response. Although $\tan \delta$ values at 0.1 Hz were similar, the rate of increase in $\tan \delta$ with frequency was much greater for DP 9370, resulting in a $\tan \delta$ value of approximately 0.1 at 100 Hz as opposed to a figure less than 0.6 for DP 85085.

7.5.5 Properties: Thermoplastic Copolyester (Hytrel)

Figure 7.9 Mean low and high strain rate tensile results TPC grades, (A) Hytrel 3078 and (B) Hytrel 3548 and (C) Hytrel 4068.

The tensile response of Hytrel TPC increases in stiffness with material grade from 3078, 3548 to 4068 respectively (Figure 7.9). Grades 3078 and 3548 displayed uniform increases in stiffness with increasing strain rate, above 0.2 strain (low strain rate results). In comparison, the 4068 grade displayed less uniform changes in stiffness for low strain rate results. The slowest strain rate (0.012 s^{-1}) was significantly more compliant than the remaining low strain rates tests, that showed minimal strain rate dependence.

The high strain rate results for the 3548 grade followed the loading profile of the low strain rate tests relatively closely, albeit the response is significantly stiffer in comparison below strains of 0.3. The remaining high strain rate results for 3078 and 4068 grades appeared initially reasonable (up to 0.3 strain) before crossing over with low strain rate data upwards of 0.4 strain.

Figure 7.10 Dynamic properties of TPC at different displacement amplitudes. Storage modulus (G'), loss modulus (G'') and $\tan \delta$ response of Hytrel 3078 (A, C), Hytrel 3548 (B, D) and Hytrel 4068 (E, F).

In comparison to the other TPE materials tested, TPC displayed a $\tan \delta$ consistently below 0.06, even though it was found to gradually increase for the lowest displacement amplitudes up to 100 Hz (Figure 7.10). Increasing the displacement amplitude beyond the linear range of the material induced a peak in $\tan \delta$ between 0.1 and 1 Hz. Consistent across all TPC grades, was a gradual increase in storage modulus with frequency,

consistent with elastomeric materials. The 3548 and 4068 material grades showed a greater sensitivity of storage modulus to increasing displacement amplitude, coincidentally exhibiting greater peaks in $\tan \delta$ between 0.1 and 1 Hz when tested with a displacement amplitude of 50 μm .

7.5.6 Properties: Thermoplastic Vulcanizate (Santoprene)

Figure 7.11 Mean low and high strain rate tensile results TPV grades, (A) Santoprene 101-55 and (B) Santoprene 101-64.

Figure 7.11 illustrates the tensile properties of Santoprene TPV. The initial stiffness is relatively low (up to 0.15 for 101-55 and up to 0.2 for 101-64) before a transition into a much stiffer region of the stress-strain profile for low strain rate profiles. After the initial low stiffness region, significant strain rate dependence was evident and distributed more evenly between strain rates for the 101-64 grade than the 101-55 grade.

The validity of high strain rate test results is questionable, with the exception of the test at 41s⁻¹ for the 101-64 grade. The results displayed a far stiffer response below 0.2 strain before the stress response plateaued, similar in nature to the high strain rate results for Alcryn 2250, implying issues existed with the testing method when testing more compliant materials.

Figure 7.12 Dynamic properties of TPV at different displacement amplitudes. Storage modulus (G'), loss modulus (G'') and $\tan \delta$ response of Santoprene 101-55 (A, C) and Santoprene 101-64 (B, D).

Santoprene TPV exhibited a storage modulus relatively sensitive to changing displacement amplitude compared to the other TPE materials. The storage modulus of both grades increased relatively steeply between 0.1 and 100 Hz (Figure 7.12). Relatively high $\tan \delta$ is also displayed by the TPV grades, although the increase with frequency (for the lowest displacement amplitude) is less substantial than the equivalent for Alcryn 2265 which has a similar $\tan \delta$ at 0.1 Hz.

7.6 Comparison with Current Ball Core Rubber

To aid the determination of potential alternative ball core materials, the TPE characterisation data were compared against the equivalent data collected for tennis ball core materials, as described in Chapter 5. Tensile data, collected at a strain rate of 1.2 s^{-1} , alongside dynamic data, collected at the displacement amplitude within the linear range of each material (Table 7.3), were selected as these provided a direct comparison of the materials.

7.6.1 Comparison of Tensile Properties

Figure 7.13 Comparison between the tensile properties of ball core rubber and TPEs (A: MPR, B: TPU, C: TPC, D: TPV); test strain rate 1.2 s^{-1}

Comparison of the tensile properties of ball core rubber and TPE materials highlighted the differences in stiffness and stress-strain profile when tested at 1.2 s^{-1} strain rate (Figure 7.13). MPR and TPV grades exhibited more non-linear stress-strain behaviour than ball core rubber, with the exception of Alcryn 2250, which was more compliant, MPR and TPV grades displayed significantly higher stresses than ball core rubber for strains greater than 0.3. At strains below 0.2 Alcryn 2265 and TPV grades were not too dissimilar to ball core rubber, with Alcryn 2265 offering very similar stress-strain behaviour.

TPC grades and Desmopan 85085 TPU were displayed considerably stiffer stress-strain behaviour than the ball core materials. The stress at 0.5 strain in the region of 6 MPa, was around double that of the equivalent for ball core rubber. The remaining TPU material, Desmopan 9370, exhibited the most similar stress-strain behaviour to ball core rubber for the magnitude of strain tested. Although the stress was in the region of 0.5 MPa larger at each point between 0.1 to 0.5 strain, the profile offered the closest representation to that of the ball core rubber. Although Alcryn 2265 provided a closer

match to the stress-strain behaviour of ball core rubber in certain areas (less than 0.2 strain), DP9370 offered a closer match across the entire range of interest.

Figure 7.13 shows the increased hysteresis, and corresponding energy loss, present in all the TPE materials examined compared to that of ball core rubber. The area enclosed by the loading and unloading stress-strain profiles, most notably for TPV but common for all TPEs tested, was considerably larger than that of the ball core materials. Furthermore, the results of tensile testing (illustrated by Figure 7.5 to Figure 7.11 for TPEs and Figure 5.12 and Figure 5.13 for ball core rubber) highlighted much greater strain rate dependence of the TPE materials tested compared to the ball core materials between strain rates of 0.12 and 6 s⁻¹.

7.6.2 Comparison of Dynamic Properties

Figure 7.14 Comparison between the dynamic properties of ball core rubber and MPR at the limit of the materials linear range. Where G' is the storage modulus, G'' is the loss modulus and tan δ is the damping factor.

Figure 7.14 compared the dynamic properties of MPR with ball core rubber. The more compliant 2250 grade of Alcryn displayed a storage modulus around half that of the pressurised ball core rubber, although the storage modulus increased at a similar rate with increasing frequency to ball core rubbers. Alcryn 2265 has a very comparable storage modulus to pressureless ball core rubber at 0.1 Hz, although it rises with frequency more steeply, surpassing that of ball core rubber at a frequency in the region of 20 Hz. The loss modulus of Alcryn 2265 had a significantly larger loss modulus than ball core rubbers, such that at 100 Hz it was comparable to the storage modulus of the

2250 grade. This results in MPR exhibiting significantly higher values of $\tan \delta$ between 1 and 100 Hz, indicating increased energy dissipation.

Figure 7.15 Comparison between the dynamic properties of ball core rubber and TPU at the limit of the materials linear range. Where G' is the storage modulus, G'' is the loss modulus and $\tan \delta$ is the damping factor.

The storage modulus of DP 9370 is comparable to Alcryn 2265 and similar in nature to ball core rubber, albeit slightly higher across the entire frequency range (Figure 7.15). The 85080 grade of Desmopan had a significantly higher storage modulus, more than double that of ball core rubber. The loss tangent showed DP 85085 to match closely the corresponding $\tan \delta$ of ball core rubber, unlike DP9370 which exhibited increased damping between 0.1 and 100 Hz.

Figure 7.16 Comparison between the dynamic properties of ball core rubber and TPC at the limit of the materials linear range. Where G' is the storage modulus, G'' is the loss modulus and $\tan \delta$ is the damping factor.

All three grades of TPC exhibited significantly larger storage modulus than ball core rubber (Figure 7.16). Storage modulus increase at a faster rate with frequency than ball core rubber, this was especially the case for Hytrel 4068. The $\tan \delta$ of all grades however is very close, and similar to that of DP850. Interestingly the softest and stiffest grade showed lower energy dissipation than intermediate grade (3548).

Figure 7.17 Comparison between the dynamic properties of ball core rubber and TPV at the limit of the materials linear range. Where G' is the storage modulus, G'' is the loss modulus and $\tan \delta$ is the damping factor.

Figure 7.17 highlights the dynamic properties of TPV compared to ball core rubber. The 101-55 grade had a very similar storage modulus to ball core rubber, falling within the pressureless and pressurised ball core materials across the majority of the frequency range. The 101-64 grade had a comparable storage modulus to pressurised ball core rubber at 0.1 Hz, however at 100 Hz the storage modulus was around 2 MPa larger. TPV grades displayed a sharper increase in storage modulus with frequency in combination with a larger and more sharply rising loss modulus than ball core rubber. This resulted in a significantly larger $\tan \delta$ for frequencies up to 100 Hz.

7.7 Discussion

7.7.1 TPE Tensile Behaviour

Comparison of the tensile properties of TPEs with ball core rubber (Figure 13) indicated TPEs exist with tensile properties spanning that of both pressurised and pressureless ball core rubber. Alcryn 2250 was more compliant, whilst TPU and TPC showed greater stiffness. Both Alcryn MPR and Santoprene TPV however, only showed greater compliance at low strains (less than 0.3), before the stresses exhibited were in excess of that of ball core rubber for a given strain magnitude.

FE models in Chapter 4 (4.6) showed strains above 0.3 accounted for less than 5% of all strain measured during impact at $52.5 \text{ m}\cdot\text{s}^{-1}$. If tensile strains above 0.3 were to be

considered to have a negligible effect on the performance of ball cores, Alcryn 2265 offered a very close match to the tensile properties of ball core rubber, particularly up to strains of 0.2. The degree of hysteresis shown by Alcryn 2265, however, is greater than that of ball core rubber and could impact on the performance of Alcryn as an alternative ball core material.

DP 9370 TPU exhibited the most similar tensile profile across the entire range of strain assessed. Although the material is slightly stiffer it did not display the highly non-linear profile of Alcryn and Santoprene, whereby the stress increases sharply above strains in the region of 0.3 strain. Likewise, with Alcryn 2265, the larger hysteresis displayed by DP 9370, in addition to the stiffer behaviour, will to some degree influence the materials performance as a tennis ball core.

Overall, TPE materials exhibited greater strain rate dependence than ball core materials when tested at low strain rates ($0.12 - 6 \text{ s}^{-1}$). Increased levels of hysteresis were also apparent, and the stress-strain profiles exhibited a higher degree of non-linearity.

High Strain Rate Testing

Issues with the reliability and validity of high strain rate test methods were determined when assessing the TPE materials. The response of the more compliant materials (Alcryn 2250, Santoprene TPV) was not in keeping with the tensile profile of low strain rate testing. It is hypothesised that due to the relatively small cross-sectional area ($2 \text{ mm} \times 6.2 \text{ mm}$) and high compliance, the materials are not able to provide a resistive response indicative of the stress response of the material. A combination of higher material stiffness and/or lower strain rate produces what appears to be a more valid representation of material stress. For example, the lowest of the high strain rate tests for Santoprene 101-64 (41 s^{-1} ; Figure 7.11B) is much more in keeping with low strain rate test results than the remaining high strain rate tests or any of the high strain rate results of the more compliant grade of Santoprene (101-55; Figure 7.11A).

High strain rate testing also displayed a drop off in stress above strains in the region of 0.4 for the stiffer of the materials tested when compared against the low strain rate data (Figure 7.7, TPU; Figure 7.9, TPC). As a result, the stresses measured at strains above 0.4 for high strain rate results were often less than or equivalent to the higher of the low strain rate results (1.2 s^{-1} , 6 s^{-1}). As strain rate dependence across TPC and TPU had been observed, it was expected that the stresses of high strain rate tensile results should be equal to or greater than that of low strain rate responses, as was the case at strains below 0.4. The nature of the test rig for high strain rate testing relied on the impact

between the drop tower and the rig to deform the sample. As a result, constant strain rate throughout the duration of elongation is dependent primarily on the impact force and the resistance to elongation of the test sample. A uniaxial load frame, as used for low strain rate tests, continuously drives the extension of the sample throughout a test, maintaining a relatively constant strain rate. The high strain rate rig does not continuously drive the extension of the sample, hence the strain rate throughout the test is not necessarily constant. With stiffer materials a greater force is required for elongation, consequently, it is hypothesised that stiffer materials (TPU and TPC) had a greater reduction in strain rate throughout the test, causing a drop off in the observed stress.

7.7.2 TPE Dynamic Behaviour

A wide variety of dynamic properties were observed when analysing TPE materials. Storage modulus ranged from as low as 1 MPa (Alcryn 2250) to 12.5 MPa (Hytrel 4068) at 0.1 Hz. Between 0.1 and 100 Hz the storage modulus of ball core rubber increased by approximately 0.5 MPa. Between the same frequencies, TPE materials displayed an increase in storage modulus in excess of 1 MPa, with some such as TPV increasing by over 2 MPa. Although the storage modulus of TPE materials increased with frequency at a faster rate (between 0.1 - 100 Hz) than ball core rubber, the storage modulus of Alcryn 2265, DP 9370 and Santoprene 101-55 were comparable to that of ball core rubber. All three of these TPEs displayed much a greater loss tangent than ball core rubber. Of the three DP 9370 offered the closest $\tan \delta$, with Alcryn 2265 and Santoprene 101-55 exhibiting a $\tan \delta$ consistently above 0.1. DP 9370 was between 0.05 – 0.1 for frequencies between 0.1 and 100 Hz, whereas ball core rubber was predominantly below 0.05.

Hytrel TPC and DP 85085 TPU displayed very similar $\tan \delta$ values across the range of frequency tested. This implies similar damping and resilience properties as ball core rubber. The storage modulus of these material grades was far in excess of that of ball core rubber however, of which the lowest was 7 MPa at 0.1 Hz.

The dynamic properties of TPEs examined in this chapter illustrates the storage modulus and $\tan \delta$ values of ball core rubber can be closely matched by TPEs, however matching both properties with a single TPE proved challenging. DP 9370 offered the best compromise with reasonable comparative storage modulus and $\tan \delta$. The general trend however found TPE materials closely matching the $\tan \delta$ of ball core rubber exhibited excessive storage modulus and TPE materials closely matching the storage modulus of ball core rubber displayed excessive damping with large $\tan \delta$ values.

7.7.3 Comparison of TPE Mechanical Behaviour to Ball Core Rubber

The mechanical and dynamic properties of the TPE materials are in general agreement. The materials with high tensile stiff were the same materials with high storage modulus (TPC, DP85085 TPU). Similarly, TPE materials exhibited similar or increased $\tan \delta$ alongside larger hysteresis than ball core rubbers. Of the TPE materials DP 9370 TPU provided the closest compromise between tensile and dynamic properties when compared to the properties of ball core rubber. Hytrel 3078 TPC offered similar $\tan \delta$ properties to ball core rubber although the tensile properties are considerably stiffer, whilst Alcryn 2265 MPR displayed very similar tensile properties (below 0.3 strain), however $\tan \delta$ values were considerably higher than ball core rubber values.

As no TPE material tested displayed the same tensile and dynamic properties as ball core rubber it is necessary to assess what impact, if any, this has regarding ball performance parameters, such as deformation, COR and contact time. This would indicate the appropriateness of any TPE material for use in ball cores and highlight potential areas in need of adjustment. Furthermore, it would highlight if the TPE ball core would conform to the ITF ball approval process.

7.7.4 Potential of TPE Materials

The TPE materials tested offered a snapshot into the properties of the wider material category. Four types of TPE and multiple grades of each have been examined and compared to the properties of tennis ball core rubber. There is considerable scope to more closely match the properties of ball core rubber through assessment of additional TPE materials and material grades as well as the chemical composition (ratio of hard and soft segments) and material formulation (compounding and cross linking).

Considerable research attention has focussed on altering the properties of TPEs. Although MPR, TPV and TPC have received some attention (Mishra *et al.* 2004, Aso *et al.* 2007, Young *et al.* 2018), TPU has seen considerable research focus (Wang and Pinnavaia 1998, Ding *et al.* 2006, Barick and Tripathy 2011, Stribeck *et al.* 2013). The number of different material suppliers offering numerous TPU grades highlights the variation in chemical composition possible, resulting in a wide variation in properties. The inclusion of nanofillers has been shown to alter the tensile and dynamic properties of TPEs. Clay nanofillers have been used to increase tensile stiffness and storage modulus, whilst decreasing $\tan \delta$ (Barick and Tripathy 2011). Tensile strength (Tien and Wei 2001), tear strength (Cheng *et al.* 2006) and gas barrier properties (Chang and An 2002) have also been enhanced by the inclusion of fillers. Consequently, great scope

exists to further modify TPE materials in an attempt to more closely match the properties of ball core rubber, should a feasible alternative be found. Altering the material would also enable gas barrier properties to be maximised, ensuring increased pressure retention, as well as potentially reducing the cost per kilogram of the material as fillers are typically less expensive than TPE materials.

7.8 Conclusions

This chapter has assessed the tensile and dynamic properties of a range of TPE materials and range of grades of each, providing an insight into the behaviour of TPEs and to what degree their behaviour is similar to that of tennis ball core rubber materials. Of the materials tested, tensile and dynamic properties of TPEs were found to closely match ball core rubber, however not by a single TPE material. TPEs with similar tensile properties exhibited higher $\tan \delta$ values than ball core rubber, whilst TPEs with similar $\tan \delta$ values were displayed overtly stiff tensile properties. The TPE materials tested displayed more non-linear and rate dependent tensile behaviour than ball core rubber, in addition to increased hysteresis.

Of the materials TPE materials tested, TPU (Desmopan 9370) provided the best compromise of tensile and dynamic properties to ball core rubber. Although materials characterisation provided an insight into the behaviour of TPEs, it does not assess how the materials would behave if applied to tennis ball cores. The determination of how a TPE ball core performs in terms of impact parameters (deformation, COR and contact time) will provide a better indication of the potential of TPEs and where properties require improvement.

Chapter 8. Finite Element Modelling of TPE Ball Cores

8.1 Chapter Overview

The FE modelling techniques developed in Chapter 6 were applied to a selection of the TPE materials previously identified in Chapter 7. Simulations provided a virtual estimation of the behaviour of the TPE ball cores during impact. The TPE ball core simulations are compared against current ball core performance measures.

8.2 Introduction

The tensile and dynamic material properties of a select group of TPEs have been analysed and compared to the rubber materials currently used in the manufacture of tennis balls. Differences in the material properties of TPEs were established, with some exhibiting similar tensile properties and other similar dynamic properties. FE modelling using the acquired material data has also been used to produce accurate representations of pressurised tennis ball cores during impact.

The time, cost and technical difficulties involved in prototyping a TPE ball core are considerable. Tooling costs to produce a mould for injection moulding would be significant and a means of fabricating half cores would be required. Further complexity is added if the TPE core is pressurised.

As a result, it is desirable to have confidence in the success of a TPE ball core prior to considerable time and financial outlay. The use of FE modelling provides an ideal environment to virtually assess the TPE materials for use as tennis ball cores and help determine if any of the materials in question are likely to perform adequately. Furthermore, FE modelling provides an environment in which the properties of TPE could be adjusted to highlight areas where performance improvements are needed if necessary.

8.2.1 Aims & Objectives

Aim: through FE modelling, assess the performance of selected TPE materials as tennis ball cores.

Objectives:

- Create TPE ball core FE models based on characterised behaviour.
- Compare TPE models to current ball core performance.

8.3 FE Model Definition

The FE model utilised in this investigation was identical to the pressurised ball core model employed in Chapter 6. The only difference being the material definition was that of the TPE material rather than the ball core rubber. When modelling the TPE ball cores the geometry of the current pressurised ball core was maintained. Due to the TPEs having a lower density than current ball core rubber the mass of the TPE models were lower than that of the pressurised core (MPR: 38.0 g; TPU: 37.3 g; TPC: 37.6 g; current ball core: 44.1 g). The reduced mass results in lower kinetic energy of the TPE cores when modelled as the lower density cores have reduced momentum. The inertia of the TPE cores are also lower than the current ball core, which would enable spin to be imparted on the ball more easily. In real terms, a reduced density core material could allow for a thicker ball core, improving pressure retention although increasing part cost, or potentially a thicker outer felt layer to improve ball longevity.

An identical approach to the material modelling of the TPE materials was taken; with the BB model utilised and calibrated against two quasi-static loading profiles (0.012 s^{-1} and 6 s^{-1}) and DMA data, collected at the limit of the linear range of material.

The TPE materials selected for FE simulation were:

- Alcryn 2265 MPR
- Desmopan DP9370 TPU
- Hytrel 3078 TPC

These TPE materials were selected based on the findings of Chapter 7, whereby the mechanical behaviour of the materials was established. Alcryn 2265 was selected as it exhibited highly comparable tensile properties, particularly at strains below 0.2. Hytrel 3078 was selected as the $\tan \delta$ was comparable to that of ball core rubber and Desmopan DP9370 was selected as this TPE offered the best compromise between tensile and dynamic properties when compared to ball core rubber.

The results of the TPE simulations were compared against the experimental data of pressurised ball core impacts (Chapter 6.4) and GOM surface strain analysis results (Chapter 4.6.1). Measures of COR, contact time, minimum normal dimension and maximum tangential dimension during impact were used to assess performance alongside strain estimations throughout the duration of impact.

8.3.1 TPE Material Models

Table 8.1 BB material model coefficients for TPE simulations.

Model Coefficients	MPR Model	TPU Model	TPC Model
mu	2083430	2206319	3156627
lambdaL	1.185235	9.999538	9.999977
kappa	5E+08	5E+08	5E+08
s	1.094827	1.093062	1.387434
xi	0.050486	0.070011	0.174736
C	-1.2312	-1.40894	-1.99998
tauBase	162150.7	1369455	1488775
m	1.199287	1.1	1.1
tauCut	0.01	0.01	0.01

The coefficients of material model calibration for TPE materials are displayed in Table 8.1. The BB model representing MPR produced a compromised response to the experimental data (Figure 8.1). Close predictions of loss modulus were experienced. A close fit and comparable profile for loss modulus had proved challenging with previous ball core rubber BB models. Similarly, the storage modulus prediction of the model had a more in keeping profile than seen previously however the overall value was underestimated across the frequency range in question. The tensile response of the MPR BB model provided an accurate representation of the higher strain rate tensile data, however the strain rate sensitivity was not well replicated.

The TPU material model produced a response more similar to that experienced with ball core rubber (Figure 8.2). Tensile properties were relatively well, although the predication of the higher strain rate data was closer than the lower strain rate prediction. Storage modulus model predications increased more gradually with frequency compared to the experimental data, such that the BB model predicted a storage modulus of approximately half the range of the experimental data irrespective of frequency. Loss modulus predictions were relatively close up to a frequency of 1 Hz, however the model did not predict the increase in loss modulus with frequency above 1 Hz.

Figure 8.3 displays the BB model prediction of TPC material behaviour was similar in nature to the equivalent TPU model. Tensile data is reasonably closely matched by the model, especially the higher of the strain rates. Storage modulus predictions are reasonable but unable to capture the change in storage modulus with frequency, instead

predicting a similar storage modulus across the entire frequency range. The loss modulus predictions are reasonable, however a trough in predicted loss modulus occurs at 10 Hz, which is not in keeping with the experimental data.

Figure 8.1 BB material model calibration for MPR. A) Tensile stress-strain prediction. B) Storage modulus prediction. C) Loss modulus prediction. D) Tangent delta.

Figure 8.2 BB material model calibration for TPU. A) Tensile stress-strain prediction. B) Storage modulus prediction. C) Loss modulus prediction. D) Tangent delta.

Figure 8.3 BB material model calibration for TPC. A) Tensile stress-strain prediction. B) Storage modulus prediction. C) Loss modulus prediction. D) Tangent delta.

8.4 TPE Ball Core Model Results

Figure 8.4 TPE ball core FE simulation results compared to experimental results for current pressurised ball core, showing (A) COR, (B) contact time, (C) normal dimension and (D) tangential dimension.

TPE ball core model results showed signs of promise when compared to the experimental impact performance of pressurised cores (Figure 8.4). MPR in particular compared favourably to the experimental data, especially for COR, contact time and tangential dimension. COR at velocities of $30 \text{ m} \cdot \text{s}^{-1}$ and below as well as contact time above $30 \text{ m} \cdot \text{s}^{-1}$ were slightly lower than experimental results, although in the main they were highly comparable. The maximum tangential deformation during impact was also highly comparable. Minimum normal dimension showed the largest difference between the MPR model and the experimental data, however the MPR model followed a similar trend to the pressurised ball core model. Normal dimension at the lowest and highest velocities were provided a closer match to the experimental data than mid-range velocities.

Both the TPU and TPC simulations predicted considerable differences with the experimental data, particularly in the case of the TPC model. COR was estimated to be significantly higher and contact time significantly lower for TPU and TPC models. The

TPC model exhibited stiffer behaviour with reduced tangential dimension. The TPC model also exhibited different trends in behaviour to the experimental data and remaining TPE models. The reduction in COR with increasing velocity displayed a more linear response for the TPC model whilst the decrease in normal dimension with increasing velocity occurred at a greater rate.

The deformation parameters of the TPU model estimated a very similar response to the MPR model, with similar measures of normal and tangential dimension. Although the COR and contact time of the TPU model displayed differences from the experimental data, the results of the sensitivity analysis performed on the pressurised core model (Chapter 6) indicate that decreasing the internal pressure of the TPU model or increasing the density of the TPU could lead to an improved representation of current ball core performance.

Comparison of the TPE simulations to surface strain analysis images further supported the similarities between the pressurised core and MPR simulations (Figure 8.5 – 8.8). Surface strain and shape profile of the MPR model are comparable to the experimental data and the most similar of the TPE models. The image series also highlight the reduced contact time predicted by the TPE simulations, particularly by the TPC model and all TPE models at $20 \text{ m}\cdot\text{s}^{-1}$. The increased deformation of MPR and TPU models perpendicular to the impact plate, resulting in reduced minimum normal dimension, was also displayed.

Figure 8.5 Comparison of pressurised ball core strain analysis to TPE simulations at 20 m·s⁻¹.

Figure 8.6 Comparison of pressurised ball core strain analysis to TPE simulations at 30 m·s⁻¹.

Figure 8.7 Comparison of pressurised ball core strain analysis to TPE simulations at 40 m·s⁻¹.

Figure 8.8 TPE ball core major strain prediction compared to measured GOM strain distribution of current pressurised ball cores.

8.5 Discussion

The results of the FE simulations of TPE ball cores highlighted the potential of MPR in particular to behave in a similar fashion to that of current ball core rubber. The measures of ball performance (COR, contact time, normal dimension and tangential dimension) compared favourable against the results of experimentally measured performance of current pressurised cores. Additionally, the shape profile and strain map of the MPR model also compared favourably against experimental data, further highlighting the potential of this material.

Areas of improvement were determined for an MPR ball core. Simulated contact time was lower than the experimental data, with the gap between the experimental data and simulation results widening with increasing impact velocity. COR at velocities below 30 $\text{m}\cdot\text{s}^{-1}$ were slightly lower compared to experimental results and may need to be increased for performance to be considered acceptable.

The TPU and TPC simulations were less similar to current ball core performance than MPR, with the TPC model in particular exhibiting significantly different behaviour in terms of contact time and COR. The shape profile of the TPC model during impact was significantly different to the experimental images, likely indicating this particular grade of TPC (Hytrel 3078) would not perform adequately as a tennis ball core. TPU results were more in keeping with the strain analysis of current ball cores, displaying a more similar deformation profile during impact. The COR and contact time however showed considerable differences to current ball core performance, suggesting the TPU in its current form would not be suitable. FE modelling results of the pressurised core highlighted a decrease in internal pressure and/or an increase in density could lead to a more comparable performance.

In addition, the MPR material model was not able to accurately capture the strain rate dependent response of MRP, resulting in a response more in keeping with ball core rubber. The loss modulus of MPR, which was larger than the ball core rubber equivalent, was accurately predicted by the BB model. In combination with underestimating the storage modulus, the MPR material model should predict a greater loss tangent ($\tan \delta$) than the ball core model, the expectation of which should reduce the COR of the MPR model in comparison. A slight reduction in COR was experienced at velocities below 35 $\text{m}\cdot\text{s}^{-1}$, which was not apparent at higher impact velocities. Arguably, a larger difference between MPR and ball core rubber was expected, and possibly not displayed due to the material model not accurately capturing the materials behaviour. Alternatively, increased loss tangent could have been counteracted by the difference in density of MPR compare

to ball core rubber (MPR: $1080 \text{ kg}\cdot\text{m}^{-3}$, Ball core: $1254 \text{ kg}\cdot\text{m}^{-3}$), since sensitivity analysis of the pressurised ball core showed a reduction in density to increase COR (6.7.1).

The experimental data against which the TPC material model was calibrated displayed considerably stiffer tensile properties and greater storage modulus than ball core rubber. As a result, the simulation results of a TPC ball core were in keeping with expectation as increased COR and reduced contact time and deformation measures were displayed relative to the other TPE ball core simulations. The TPU ball core model was in keeping with the results of MPR and TPC simulations. TPU displayed material properties in between that of MPR and TPC for tensile stiffness, storage modulus and loss modulus. As expected, the COR, contact time and deformation measures of the TPU simulations were between that of the MPR and TPC models, although the deformation profile of TPU was more similar to MPR than TPC when comparing surface strain (Figure 8.5 – 8.8).

Based on the experimental data used to calibrate the material models for TPE materials, the trends in behaviour of the TPE ball cores are in keeping with expectation. Differences between the TPE and ball core materials from a materials characterisation view point are portrayed by the results of the simulations.

Although promising, the results of TPE ball core modelling should be assessed in context. The modelling techniques, in particular the material model and data the model was calibrated against, have been shown to produce an accurate representation of a pressurised tennis ball core during impact (Chapter 6). It was therefore assumed that the approach was applicable to TPE materials, which based on the similarity of the tensile and dynamic material properties of the materials and that the BB model has been shown to accurately capture the behaviour of a range of elastomeric materials (Bergström and Boyce 1998, 2000, Bergström 2015), would appear a reasonable assumption.

The desire for utmost accuracy highlights the closeness of fit of the BB model to the experimental material data. As was the case for ball core rubber, an exact match of both the tensile and dynamic data was not achievable. The BB model was again shown to compromise between the inputted test data. The representation of the MPR material highlighted the inability to accurately represent the strain rate dependence displayed by the test data. Furthermore, the model underpredicted storage modulus, although it produced the closest prediction of loss modulus of all the BB model calibrations presented in this thesis.

In addition, FE simulations provide a prediction of the proposed scenario based on the information provided. In being a prediction and estimation of reality, the accuracy of the

model will not truly be established until compared against a real-world equivalent. The results of the TPE models however provide additional confidence that the route of employing TPEs to the application of tennis ball cores would appear plausible and worthy of additional attention. Had the results of the TPE models produced significantly different performance to that of the current materials, the likelihood of further time and financial investment in assessing TPEs would be reduced. As it stands the results presented indicated that TPEs, in particular the MPR grade modelled, is worthy of further investigation. A logical next step would be to produce a limited number of MPR ball cores, potentially unpressurised for simplicity, and experimentally assess the impact performance against a de-pressurised ball core.

8.6 Conclusions

The TPE ball core simulations presented offered a promising insight in to the potential of a TPE tennis ball core. The ball core model incorporating Alcryn MPR performed favourably when compared to experimental data from pressurised ball core impacts, producing highly comparable COR, contact time and deformation results, indicating potential as a ball core material.

TPU and TPC models produced simulations with larger COR and reduced contact time than experimental ball core results. The TPU model produced a deformation response more in keeping with the experimental data than the TPC model and may be able to be manipulated, through reduced internal pressure or increased density, to produce a closer match to current ball core performance. The TPC material however, does not appear applicable for use in tennis balls.

Chapter 9. Discussion

9.1 Chapter Overview

The research aims and objectives detailed in Chapter 1 have been addressed with reference to the findings of entire body of research presented. The findings and limitations of the research are discussed.

9.2 Discussion in Relation to Research Aims

Establish a materials characterisation test methodology, representative of the conditions a ball experiences during use, against which TPE materials can be directly compared to current ball core rubber.

The body of work presented in this thesis has described techniques and methodologies capable of assessing current and potential alternative TPE materials for use in tennis ball cores, with the future aim of improving tennis ball core design. The testing methodologies and techniques relate back to analysis of ball impact conditions, which ensured assessment of materials and their behaviour was targeted, representative of the impact conditions experienced during professional tennis, and quantified the range of properties experienced.

Replication of typical ball impact conditions in the laboratory provided a means of transferring from dynamic ball impacts to representative materials characterisation testing through use of non-contact strain measurement techniques. The measurement of strain and strain rate during impact quantified the extremes of desired material characterisation tests, such that ball core material could be tested to the limits required by the application. As a result, the testing of ball core material can now be targeted and representative of what is experienced during play. Additionally, non-contact strain measurement techniques provided a further, more visual, means for validating FE simulations in addition to more standardised impact measures. Surface strain mapping provided a comparison throughout impact duration, enabling the localised assessment of FE simulations as opposed to overall measure of performance, such as COR and contact time.

The use of standard test equipment (ElectroPuls, DMA) provided a consistent and reliable means of establishing tensile and viscoelastic material properties. The major benefit of the ElectroPuls being the increased strain rate capability over traditional screw-based test frames, enabling intermediate strain rates ($\approx 1\text{-}10\text{ s}^{-1}$) to be achieved.

Difficulties were encountered when testing at high strain-rates. Although the developed test rig was capable of higher strain rates than standard equipment, the rates achieved did not reach the highest rates observed during impact and the results obtained were not robust; appearing sensitive to the tested sample. Overall, the material data gathered was insightful and provided a measure to compare TPE materials against, albeit not across the entire strain rate range of interest. In addition, the data captured proved adequate in its ability to supply FE simulations with an appropriate material definition.

Characterise current ball core materials and potential TPE alternatives to assess similarity and identify potential alternative TPE materials for assessment as a tennis ball core.

TPE materials have been identified as potential ball core materials, offering possible benefits over current ball core rubber. As well as possible pressure retention capability, which could lead to improved product life span, TPEs offer manufacturing and end of product life cycle advantages. The ability to manufacture tennis balls using conventional plastic processing techniques (e.g. injection moulding) would reduce the labour-intensive nature compared to current rubber production, which could lead to localised manufacturing and reduced transportation costs. The thermoplastic nature of TPEs offer potential recyclability benefits of conventional vulcanised rubbers. Currently, tennis balls cannot be recycled. TPEs offer the opportunity to produce a recyclable ball core, which could be reclaimed and reintroduced into a new batch of tennis balls.

Despite the potential benefits of TPEs, the viability of a TPE ball core would need to be established from a business standpoint to ensure the product could be profitable, since the unit cost of TPE is likely higher than that of rubber. In addition, acceptance from players and their perceptions of a new ball would impact any new products success. The underlying and most important question however, was could current ball performance be matched when using a TPE core material?

Groups of TPEs were identified as having properties somewhat similar to that of natural rubber and specific grades of MPR, TPU, TPC and TPV were sourced. In general, the TPEs tested displayed increased nonlinearity, hysteresis and strain rate dependence when compared to ball core rubber at the conditions tested.

Materials characterisation tests alone offered an insight into the performance of TPE materials, where in part, the behaviour of ball core rubber matched closely. No one single TPE tested however proved a perfect match to ball core rubber when assessing tensile and dynamic behaviour. MPR was found to closely match the tensile behaviour at low strains (< 0.25 strain) but displayed significantly greater strain rate dependence

and damping properties. TPC was found to have a very similar $\tan \delta$ response to changes in frequency but was significantly stiffer in tension. TPU offered a response between MPR and TPC, however neither material was perfect match for ball core rubber, nor did materials characterisation alone determine how the materials would behave as a ball core. The materials tested are a minute subset of the TPEs commercially available, with the possibility to further tune a given materials properties using fillers, additives or blending. As a result, a closer match to ball core rubber than the TPEs tested is certain to exist.

Develop a finite element model to predict and compare the behaviour of current ball cores to TPE alternatives during impact.

FE simulations of TPE ball cores highlighted promising performance compared to the experimental impact data of a pressurised ball core. Impact performance measures; COR, contact time, minimum normal dimension and maximum tangential dimension of the MPR simulations compared favourably, as did surface strain analysis and deformation profile throughout impact duration. Although this does not guarantee MPR will perform adequately as a ball core, it indicated MPR has shown potential and is worthy of further scrutiny. A logical step would be to prototype an MPR ball core and experimentally assess its performance, whilst acting as validation of the FE simulation.

Assessment of impact conditions and impact performance provided the groundwork for assessing material behaviour for characterisation and FE modelling purposes. Materials characterisation provided the fundamental mechanical material properties which FE modelling successfully implemented. The FE simulations were able to successfully incorporate the mechanical properties of pressurised ball core rubber, utilising relatively limited experimental data, to accurately predict pressurised ball core performance. Tensile loading profiles at two strain rates (0.012 s^{-1} and 6 s^{-1}) and a DMA frequency sweep provided adequate information to produce an accurate model. The adopted modelling approach expanded on previous work by incorporating experimentally determined multi-strain rate and viscoelastic material behaviour through use of a viscoplasticity material model (BB model). The BB model enabled the non-linear, time-dependent behaviour of ball core rubber to be encapsulated within a single, more advanced, material model. The need to tune model parameters against test data to improve model correlation was also avoided.

The approach determined to assess ball core materials offers a concise, fast and representative methodology through minimal material characterisation and FE modelling. The inputs can be changed with relative ease to assess potential alterations, be it

internal pressure, stiffness, damping properties or even dimensional changes. The same degree of flexibility when testing physical prototypes would prove financially costly in comparison.

Difficulties were encountered in accurately predicting the performance of the pressureless ball core. In addition, the accuracy of deformation normal to the impact surface could be improved. Further enhancement of the material model calibration or the investigation of other viscoplasticity models could lead to improved model accuracy.

Chapter 10. Conclusions & Recommendations for Further Work

10.1 Chapter Overview

The findings of the research are presented and potential areas for future work identified.

10.2 Conclusions

The work presented in this thesis has identified TPEs as potential alternative materials for tennis ball cores, based, as closely as possible, on experimental data produced under conditions representative of professional play. Replication of impact conditions alongside DIC strain measurement techniques were utilised to inform materials characterisation testing. In turn, enabling the production of a simulation methodology capable of accurately representing a pressurised ball core during impact, which was utilised to assess the performance of a select group of TPE materials. Although not definitive proof a TPE material is capable of matching the performance of current ball cores, evidence of similarities in TPEs and ball core rubber behaviour have been determined, indicating TPEs are worthy of further attention and scrutiny for use in ball cores.

Novel use of ball tracking data from professional tennis matches, played across the major court surfaces, was utilised to establish typical impact frequencies and conditions experienced by the ball during the nine games of play it is subjected to. Furthermore, differences between the ITF durability test methodology and in-play measures highlighted the need for a durability test capable of assessing the lifespan of a given ball in a way that corresponds to length of play. The ITF durability test was considered fit for purpose for the task of a pass-fail criterion, however, it was not deemed representative of professional play or applicable for evaluating ball lifespan.

Examination of ball tracking data was successful in informing representative impact conditions for laboratory testing of ball impacts against a rigid surface. A mean impact condition was established, with the ball impacting the surface at angle of 19° to the surface at a speed of $22 \text{ m}\cdot\text{s}^{-1}$. Maximum ball speed occurred during serves, with speeds in excess of $50 \text{ m}\cdot\text{s}^{-1}$ observed.

Inferred impact conditions were replicated to physically measure the strains and strain rates present during impact using non-contact DIC software. The first reported measurement of strain and strain rate during impact were compared to previously

developed FE simulations as a means of validation. Under the most severe impact conditions tested (90° , $52.5 \text{ m}\cdot\text{s}^{-1}$), maximum strains of 0.4 in tension and -0.4 in compression and maximum strain rates of 600 s^{-1} in tension and -800 s^{-1} in compression were observed. DIC techniques were inhibited by extreme deformation observed at the most severe impact conditions (90° , $\geq 43.1 \text{ m}\cdot\text{s}^{-1}$), resulting in incomputable impact frames.

Materials characterisation testing saw the novel assessment of pressurised and pressureless ball core rubber from low to high strain rates (0.012 s^{-1} – 84 s^{-1}) to a strain magnitude of 0.5, successfully indicating limited strain-rate dependence across the range of strain rates tested. A bespoke test rig in combination with an impact drop tower was utilised to assess high strain rate mechanical behaviour. The first reported assessment of ball core rubber viscoelastic properties was established using DMA, providing an assessment of the dynamic stiffness and damping properties of the material. Characterisation testing highlighted the similarities between pressurised and pressureless ball core rubber compounds, despite the lack of assistance from internal pressure for the global stiffness and performance of pressureless ball cores.

Advances in material modelling enabled the development of a novel FE model incorporating multi-strain rate tensile data, to capture the strain rate dependent material behaviour. Additionally, DMA data was incorporated to include the viscoelastic properties of the material, which for the first time in tennis ball modelling, was based on experimental data, eradicating the need for artificial model tuning. The BB viscoplasticity material model was successfully implemented to produce an accurate representation of the pressurised ball core during impact, although poor representation of the pressureless core model was achieved. Sensitivity analysis of the ball core models highlighted the effect of changing internal pressure, material density and tensile stiffness on ball core performance, in particular on COR and contact time.

TPE materials were identified as possible alternatives to vulcanised rubber, capable of displaying elastomeric material properties with the potential benefits of thermoplastic manufacturing processes, recyclability and improved pressure retention properties. By subjecting a range of TPE materials to the materials characterisation techniques developed, properties similar to ball core rubber were exposed. Of the materials tested, tensile and dynamic properties of TPEs were found to closely match ball core rubber, however not by a single TPE material. TPEs with similar tensile properties exhibited higher $\tan \delta$ values than ball core rubber (MPR), whilst TPEs with similar $\tan \delta$ values were displayed overtly stiff tensile properties (TPC). The TPE materials tested displayed

more non-linear and rate dependent tensile behaviour than ball core rubber (at strain rates between 0.012 s^{-1} and 6 s^{-1}), in addition to increased hysteresis.

MPR, TPU and TPC were subjected to the FE modelling methodology developed for ball cores, with MPR performing favourably when compared to experimental data from pressurised ball core impacts; producing highly comparable COR, contact time and deformation results, indicating potential as a ball core material. The TPC model did not appear suitable as a ball core material, resulting in overly short contact time and increased COR compared to core impact results. The TPU model predicted a response between that of the MPR and TPC model, with the potential to correspond more closely to ball core performance through a reduction in internal pressure and/or increase in density.

10.3 Recommendations for Further Work

An alternative means of testing the high strain rate response of elastomeric materials would be desirable, such that that vibration and noise in the system does not inhibit the capability of the rig to capture at the highest rates observed during impact (600 s^{-1}).

Further research utilising viscoplasticity material models and combinations of experimental data could lead to improved model accuracy for pressurised and pressureless ball cores. This would enable optimisation of the testing and modelling process through improved understanding of how the combinations of experimental test data and available models affect model accuracy.

This FE modelling presented in this body of work has focussed exclusively on normal ball core impacts. Expanding into more complex impact scenarios by incorporating oblique impact angles and spin could lead to improved understanding of ball performance and a more thorough assessment of potential alternative materials. Additionally, impacts incorporating the felt and impacts with a racket would further enhance understanding.

Further scrutiny of TPE materials, especially MPR, through ball core prototyping, would continue to establish the material's potential for use in tennis ball cores and help identify any necessary areas for improvement. It would also act to validate the FE simulations of TPE cores and confirm if the modelling approach is transferable between materials. Incorporation of the felt to assess the ball as complete system would also be necessary. A combination of modelling and testing could be used to determine the range of properties a ball core must possess in order to pass the ITF ball approval process.

Optimisation of TPE materials deemed to perform adequately as a ball core material is worthy of consideration. Investigations into the use of additives, such as fillers, and material blending should be investigated as a means of producing more comparable impact performance to current ball core materials. Additionally, the use of fillers could lead to further improvements in pressure retention capability as well as reducing material costs.

Factors other than purely performance-based measures should also be assessed. Should a TPE be incorporated into an approved ball, the manufacturing process would need to be determined, as would whether or not the product is viable from a business perspective. Furthermore, player perceptions of a new ball should be assessed to ensure the product is to the players liking.

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