Elastomeric shockpads for outdoor synthetic sport pitches

ELASTOMERIC SHOCKPADS FOR OUTDOOR SYNTHETIC SPORTS PITCHES

By

Lauren Anderson

A Doctoral Thesis submitted in
partial fulfilment for the degree of
Doctor of Philosophy
of Loughborough University.

14th September, 2007

Abstract

This thesis identified key mix design variables that influence the mechanical properties and behaviour of shockpads and developed a mechanical model to describe this behaviour.

This investigation was undertaken to address the lack of scientific understanding of shockpad layers used in synthetic sports pitches. Shockpads play a crucial role in the player and ball interaction properties of synthetic pitches. However, the current poor state of knowledge regarding shockpad mix design effects and the implications for site practice during construction was developed through constructor experience and basic testing. This lack of comprehensive knowledge was reflected in the barely-existent standards for design specification and testing requirements stipulated by sporting governing bodies at the time of this project inception. Further scientific investigation of the effects of shockpad mix design on mechanical properties and behaviour was required to develop guidelines to optimise shockpad design, construction and testing and also to build more knowledge on sport surface behaviour due to growing interest among the industry and other stakeholders such as governing bodies and sport shoe manufacturers for example.

A method to construct small-scale cast in-situ shockpads in the laboratory was developed to produce reliable and repeatable samples for investigation, including a benchmark shockpad and shockpads with carefully controlled mix design variations. Shockpad thickness, binder content, binder type, rubber size, rubber size distribution and bulk density were varied through a range of appropriate values in the laboratory constructed shockpads. Shockpads and shockpad-carpet systems (using water based and 3rd generation carpets) were subjected to Berlin Artificial Athlete and 2.25 kg Clegg Hammer impacts to measure player-surface interaction properties and vertical hockey ball impacts to measure ball interaction properties. Tensile measurements and cyclic fatigue testing were used to determine shockpad durability. Impact testing was repeated on shockpads and shockpad-carpet systems with thickness variations to determine shockpad behaviour using a force plate. Behaviour measurements were used to develop a mechanical model to describe shockpad behaviour.

Shockpad thickness was shown to be a key mix design variable for player and ball interactions. Bulk density, rubber size and size distribution and binder type were shown to be secondary variables for player interactions. All variables, particularly binder content and thickness, were shown to affect shockpad durability. When subjected to a compressive impact, shockpads exhibited a non-linear force-deflection relationship with hysteresis. Shockpad behaviour could be divided into three distinct phases; air void compression, transition and rubber compression. Increasing shockpad thickness reduced peak impact forces and final stiffness. The carpet layers used in shockpad-carpet systems reduced peak impact force, stiffness and energy return. The different ball and simulated player and ball impacts also influenced peak impact force and stiffness exhibited by the shockpad. The non-linear damped model was able to accurately describe the loading and unloading behaviour of ball and simulated player impacts. Simulated accelerated mechanical degradation demonstrated how shockpad mechanical properties will change over time through permanent thickness reduction and loss of bonds between rubber and binder.

Based on research findings, recommendations are made to shockpad manufacturers and relevant sporting governing bodies for increased shockpad mix design specification, improved measures to control mix design during construction and site testing to verify mix design specification have been met. Shockpad behaviour measurements and the mechanical model used to describe this behaviour will further understanding of the behaviour of whole synthetic pitches and assist research into the development of models describing the interactions between players and synthetic sports pitches. The improved understanding of the shockpad layer of synthetic sports pitches is expected to improve consistency among synthetic pitch constructions which will ultimately benefit synthetic pitch users.

Keywords: Shockpad, Synthetic Sports Pitch, Design, Mechanical Property, Mechanical Model, Testing

Acknowledgements

To my supervisors, Dr. Paul Fleming and Dr. Ali Ansarifar, I am deeply grateful for the guidance and support you have offered throughout the course of this research project. I could not have imagined better mentors to keep me on the right track, your knowledge and enthusiasm and has been great source of inspiration.

I wish to thank the Department of Civil and Building Engineering, Loughborough University and the industrial collaborators - Aggregate Industries, Murfitts Industries and Polytan Sports Surfaces for their financial support of this project. In particular, I would like the thank Bob Allen, Carly Denton, Barry Stoker and Andy Shaw for their significant contribution to my understanding of the shockpad construction industry through the lively discussions at project steering meetings.

I also wish to acknowledge the support I have received from the staff of both the Civil Engineering Department and IPTME. In particular, Mark Harrod, Alex Harrison and Dave Spendlove in the Civil Labs and Ray Owens in the IPTME Labs, for their assistance and patience during my time spent developing and conducing (at times hazardous!) testing.

To my fellow research students in Civil Engineering and IPTME, there are too may of you to mention individually, but your support and friendship has really made me feel at home in this foreign land. Colin Young and John Lambert, you both stand out, thank you for always having the time to discuss work matters and for some memorable lunches. To James Dennis, a great friend when I needed one, thank you for all the support you have given me over the last few years and the memorable holidays that provided a great break from the work.

Finally, thank you to my parents, Peter and Janice Anderson, for having the faith in me to let me go out into the world and realise a dream.

Table of Contents

Contents *Page No.*

List of Figures

Figure *Page No.*

List of Tables

Table *Page No.*

Chapter 1

INTRODUCTION

1.1 Background

Synthetic sports pitches were introduced in the 1960's and have since steadily increased in popularity among sporting clubs and schools. These synthetic sports pitches benefit from their ability to be used all year round, lower maintenance requirements and more consistent and repeatable performance characteristics than natural turf pitches. The transition from natural to synthetic surfaces is most apparent for the game of hockey, where synthetic surfaces are now a requirement for higher lever competitions (FIH, 1999). For football and rugby this transition has been much slower. However, developments in the 1990's of 3rd generation pitches that uses a rubber in-fill between carpet fibres to reduce friction burns to players has prompted trials for the use of synthetic pitches in European football matches and the installation of synthetic rugby pitches in England. A future generation of sports players accustomed to synthetic sports pitches at school and continued specification by sporting governing bodies will surely lead to further installations.

There are a wide variety of synthetic sports pitches currently available that are designed specifically for certain sports or for multiple uses. Many of these, particularly those specified for hockey, football and rugby are of similar structure, comprising foundation layers, a shockpad and synthetic carpet. The main distinction between pitch varieties is the rigidity of the foundation layers, the type and thickness of the shockpad and the pile height and in-fill materials used in the carpet.

The shockpad layer of a synthetic sports pitch provides shock absorbency for users of the pitch for both comfort and safety and allows the foundation and carpet layers to absorb and restore impact energy to produce the required ball rebound characteristics. There are three main varieties of shockpad; cast in-situ bound rubber crumb, prefabricated bound rubber crumb and integral shockpads. Integral shockpads are constructed from closed cell foam and attached to the underside of the carpet during manufacture. Bound rubber crumb shockpads, cast in-situ and prefabricated, are constructed from a mixture of recycled rubber particulate and polyurethane binder compacted into a continuous layer. The prefabricated shockpad is constructed in a factory environment, where conditions are considered more controllable relative to cast in-situ shockpads. However, when laid on site, prefabricated shockpads must be adhered to the foundations to prevent gaps or ridges forming at the seams due to shrinkage, expansion or movement of the layer. Cast in-situ shockpads are the most popular variety of shockpad currently installed in UK as they are able to be laid on-site to form a continuous layer and account for small inconsistencies in the foundation layer. However, this variety is subject to variations in on-site construction methods and cure environment.

The shockpad layer plays an important role in the player and ball interactions of a synthetic sports pitch, however the current state of knowledge regarding shockpad design and site practice during construction was a result of constructor experience and basic testing. Young (2006) showed shockpad thickness to have a significant effect on both the shockpad and whole pitch mechanical properties, however these findings are not reflected in the barely-existent standards for design specifications and testing requirements stipulated by sporting governing bodies. Further scientific investigation of the effects of shockpad design on mechanical properties and behaviour is required to develop guidelines to optimise shockpad design, construction and testing. Additional shockpad mechanical property data is also required to assist academic research into measuring player-surface and ball-surface interactions.

1.2 Aims and Objectives

This research project aims to quantify key mix design variables that influence the mechanical properties and behaviour of shockpads to promote good site practice for shockpad construction and contribute to current academic research into modelling player-footwear-surface interactions. These aims are achieved through a number of objectives, outlined below.

1. To characterise the recycled rubber particulate used to construct shockpads

2. To investigate the effect of mix design variables on mechanical properties corresponding to durability and player and ball interaction characteristics for shockpads

3. To determine the impact behaviour of shockpads in response to ball and simulated athlete impacts and develop a mechanical model to describe this behaviour

4. To develop guidance for the synthetic pitch construction industry and sporting governing bodies in the areas of design, construction and quality control testing of shockpads

1.3 Research Philosophy

This thesis aims to address the current lack of knowledge within the synthetic pitch construction industry regarding the effect of mix design on shockpad and shockpad-carpet system mechanical properties. The experimental methodology used in this research project was therefore required to replicate the shockpad constituent materials, design, construction and testing process used for on-site synthetic pitch constructions to provide findings directly relevant to the industry.

The current state of knowledge within the shockpad construction industry was based on empirical relationships between mix design and mechanical properties gained through constructor experience. A scientific approach was required to quantify the effect of shockpad mix design variables on mechanical properties to provide an accurate identification of key mix design variables requiring careful specification and control during construction. However, cast in-situ shockpads are large-scale constructions that were not capable of providing sufficient accuracy and control of mix design variables for the requirements of this investigation. Therefore, a small-scale laboratory construction method was developed that allowed each mix design variable to be accurately controlled. The method was limited in its ability to allow all mix design variables to be varied, however, it was considered appropriate as it allowed the majority of mix design variables to be examined, particularly those such as thickness, bulk density and binder content, which were expected to produce the most significant effect.

A benchmark shockpad was required to be developed to provide an example of the typical mix design of shockpads produced on-site and subsequent shockpads constructed with variations in mix design to quantify the effects of poor practice during construction. A 'typical' mix design was not specified in literature and therefore required industrial collaboration and characterisation of samples taken from shockpad construction sites to determine the appropriate design specifications for the benchmark shockpad. Ranges of variation for each mix design variable were also required to be developed, and was achieved through industrial collaboration.

Mechanical test methods were used to measure the effects of mix design variations as they presented a repeatable and comparable method that human subject testing was not able to provide. The mechanical test methods were limited in their ability to measure changes due to player mass and movement velocity and ball interactions occurring at various velocities and angles. However, industry standard test methods were used alongside alternative test methods to determine the most accurate simulation of in-service conditions.

The scope of this research project was predominantly focused on the effect of mix design variables on the shockpad layer of synthetic pitch constructions and was intended to form a sound understanding of their basic properties and behaviour. However, as the shockpad forms a composite system with the carpet layer in whole pitch constructions, the effect of shockpad mix design variables on mechanical properties and behaviour for shockpad-carpet systems was also of interest. Testing a wide range of the carpets commercially available was not considered within the scope of this project and therefore two generic carpet systems, one water based hockey carpet and one 3rd generation football/rugby carpet was selected to represent the carpet layer of the synthetic pitch.

A basic mechanical model was also developed to describe shockpad and shockpad-carpet system behaviour as it presented the logical first step to producing an accurate model. The development of a more complex numerical model, which would be potentially capable of describing the strain gradients produced around the shockpad thickness during an impact, was not considered within the scope of this research project due to a lack of sufficient behavioural data contained in previous published research.

The methodology of this investigation was focused on the cast in-situ shockpad as it was identified as the most common variety installed for synthetic pitches in the UK. However, the findings and recommendations are also applicable to prefabricated shockpads and in general any bound rubber crumb installations for other applications, such as for playground and walkway surfaces for example, as they are based on similar mix design and construction principles.

1.4 Thesis Outline

Details of how each chapter is interlinked is presented in Figure 1.1. The literature review (Chapter 2) was used to identify key research needs and form projects aims and objectives that are outlined in the Introduction (Chapter 1). Chapters 3, 4 and 5 form individual sections of research within the thesis, each containing its own introduction, experimental methodology, results, discussion and summary of findings. Chapter 6 outlines the findings from Chapters 3 to 5, providing a discussion of the main research findings and how they address the key research needs identified by the literature review. Chapter 7 provides concise conclusions and recommendations for the thesis. A brief summary of contents of each chapter contained within this thesis is provided in the following sections.

Chapter One provides an introduction to shockpads used in outdoor sports pitches. It highlights the current lack of knowledge and scientific investigation of this topic, and identifies areas in need of research used to develop the aims and objectives.

Chapter Two presents a critical review of published literature relating to synthetic sports pitches and shockpads layers, focusing on cast in-situ shockpads. This chapter discusses the current state of knowledge and details key research needs in the area of shockpads used in outdoor sports pitches.

Chapter Three characterises recycled rubber particulate used to construct shockpads by quantifying the variability contained within a typical batch of recycled rubber particulate in terms of composition and physical and mechanical properties.

Chapter Four measures the effect of mix design variables on the mechanical properties of cast in-situ shockpads and shockpad carpet systems in terms of player and ball interactions and durability.

Chapter Five examines the force-deflection and stress-strain behaviour of shockpads of varying thickness for ball and player impacts. The shockpad behavioural data, collected using a force plate, was used to develop a mechanical model to describe the shockpad behaviour.

Chapter Six presents a summary of how the research findings from each chapter link together to discuss and clearly identify factors which influence shockpad mechanical properties and behaviour.

Chapter Seven presents concise conclusions and recommendations for both areas of further research and for industry. The chapter also provides a summary of the contribution this research project has made to furthering academic and industrial knowledge.

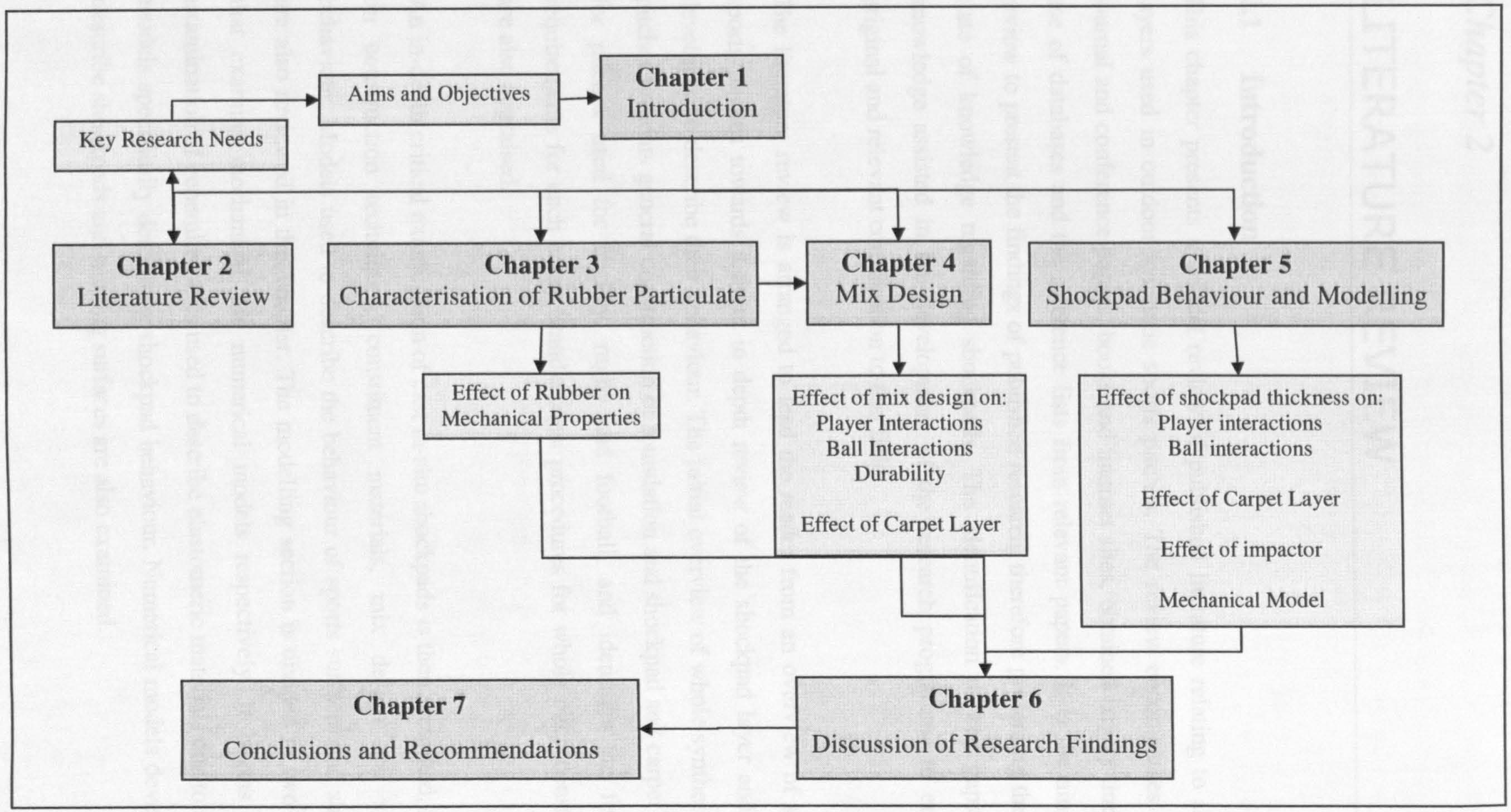


Figure 1.1: Flow diagram of interaction between thesis chapters

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a critical review of published literature relating to shockpad layers used in outdoor synthetic sports pitches. The review encompasses relevant journal and conference papers, books and internet sites, obtained largely through the use of databases and the reference lists from relevant papers. It is the aim of this review to present the findings of published research, therefore presenting the current state of knowledge regarding shockpads. The identification of key gaps in this knowledge assisted in the development of the research programme to ensure an original and relevant contribution to this field.

The literature review is arranged to lead the reader from an overview of synthetic sports pitches towards a more in depth review of the shockpad layer and models developed to describe their behaviour. The initial overview of whole synthetic sports pitches presents general construction of foundation and shockpad and carpet systems for pitches used for hockey, rugby and football, and identifies the functional requirements for each layer. Standard test procedures for whole pitch constructions are also appraised.

An in-depth critical examination of cast in-situ shockpads is then presented, focusing on construction techniques, constituent materials, mix design and shockpad behaviour. Models used to describe the behaviour of sports surfaces and shockpads are also reviewed in this chapter. The modelling section is divided in two sections that examine mechanical and numerical models respectively. It begins with an examination of general models used to describe elastomeric materials due to a lack of models specifically describing shockpad behaviour. Numerical models developed to describe shockpads and running surfaces are also examined.

A critical discussion of key points raised by this review regarding shockpad mix design, constituent materials, quality control testing, shockpad behaviour and modelling concludes this chapter. This discussion highlights areas in need of further research that form the basis of aims and objectives for this investigation. A short summary also provides an overview of literature review findings.

2.2 Synthetic Sports Pitches

This section provides an overview of the published literature regarding synthetic pitches for hockey, football and rugby. The overview encompasses the design and functional requirements of foundation, shockpad and carpet layers, loading of synthetic pitches, in-service environmental conditions and an appraisal of test methods stipulated by sporting authorities to ensure whole pitch structures demonstrate correct performance characteristics for the intended sport.

2.2.1 Design and Functional Requirements

Synthetic pitches are designed specifically for individual sports or as Multi Use Games Areas (MUGAs). Both types of pitch are composite structures, formed from layers of various materials, as shown in Figure 2.1. The three major components of a synthetic sports pitch are the foundation, shockpad and surfacing layers. Foundation layers are composed of a stone sub base composed of crushed stone and macadam layers, and at times used to provide additional rigidity below the surfacing layers. The shockpad layer is typically an elastomeric layer used in combination with a synthetic carpet to produce specific ball and player interaction characteristics. The foundation, shockpad and carpet layers are distinguishable by their role in pitch performance and the materials used for their construction. Each layer of the pitch structure performs a specific task, the foundation layers provide a stable and rigid base while the shockpad and carpet layers control player and ball interaction characteristics. The foundation, shockpad and surfacing systems are reviewed in detail in the following sections.

2.2.1.1 *Foundation Layer*

The foundation is required to support and transmit all subjected loads without causing any permanent deformation to the site (Tipp and Watson, 1983) and to create a level surface that will not unduly influence the path of a ball (Abbott, 2003). It must possess sufficient porosity to allow the drainage of surface water (FIH, 1999; Tipp and Watson, 1983) and also provide resistance to frost damage and moisture (Fleming, Dixon, Lambert and Young, 2002). Foundations must be capable of fulfilling these requirements adequately throughout their service life. Specifications for longevity are not stipulated by any sporting authorities, but standard lifetime for this type of construction is expected to be at least 25 years (Fleming et al, 2002; Tipp, 1993), which is about 2-3 times longer than the surfacing system, and must therefore be a strong and durable layer.

The loads applied to sports pitches are from construction and maintenance vehicles, static equipment such as goals and those imposed by players and balls (Abbot, 2003; Fleming et al, 2002). These loads generally apply a shear force to the surface which can be transferred to the foundation. It is recommended by UEFA (2003) that the load bearing capacity of the foundations for synthetic sports pitches are 60 to 70 MPa for the wearing course and 40 to 45 MPa for the sub base. UEFA provide no reference to the method used to determine the load bearing capacity of foundation layers. No references quantifying the magnitude of loads transferred to the foundations through the surfacing layers could be found to support or refute the recommendations provided by UEFA.

Many foundation construction details described in the literature are similar, with differences generally only in the macadam layers. Some common foundation designs are shown in Figure 2.2, where distinctions are made by the extent to which they are engineered. Designations of dynamic, semi-bound or bound are given to foundation types. Dynamic foundations are designed to act more like natural turf pitches with the foundation providing shock absorbency and therefore influencing ball and player interactions (Watson, 1986; Crawshaw 1989). Bound bases are relatively rigid and generally rely on the incorporation of a rubber shockpad to produce the required playing characteristics (Tipp and Watson, 1983). They are claimed to have a superior durability to other foundation types (Harrison, 1992; Crawshaw, 1992).

Some contention exists on the subject of the best foundation for synthetic surfaces. It is advantageous that generally unbound foundations are cheaper to construct than engineered constructions of similar depth. It is also claimed they provide a more 'natural feel' to the playing surface because of its ability to deform under impact, (Watson, 1986; Crawshaw 1989). The grade of stone and degree of compaction requires careful consideration as they have a profound effect on the playing characteristics of the surface (Tipp and Watson, 1983). However, it has been identified that the use of these foundations is declining as the financial savings of omitting the macadam has not justified the reduced life and inferior product (Harrison, 1992) and are not recommended for use in football surfaces (UEFA, 2003). These pitfalls have been attributed to the quality of workmanship rather than the product itself (Tipp, 1992)

2.2.1.2 Shockpad Layer

Functional Requirements

Shockpads play an important functional role in the safety, player interaction and ball interaction characteristics of synthetic sports pitches. Few references have specifically elaborated on these requirements for shockpads. Dixon et al (1999) details properties such as shockpad stiffness and resilience as influencing factors in pitch playing characteristics and the potential for injury, while Breland (1990) states shockpads must be designed to provide comfort and cushioning to players throughout a range of weather conditions.

Shock absorbency of a pitch system is commonly attributed to the shockpad layer. It is described by Breland (1990) as the ability of a surface to spread out the contact time and reduce the peak force of an impact. Researchers commonly interchange between terms of shock absorbency, stiffness, compliance, comfort, cushioning hardness when referring to this ability to reduce the peak impact forces and spread out the contact time of an impact. Few researchers have examined factors in shockpad design that can alter shock absorbency. Young (2006) altered shockpad thickness between 6 and 20 mm and measured a 20% increase in force reduction measured with a Berlin Artificial Athlete (detailed in Section 2.2.5) and 300g reduction in peak deceleration by impacting them with a 2.25 kg Clegg Hammer. Both tests demonstrated a reduced peak force, and therefore increased shock absorbency, by increasing shockpad thickness. Dixon et al (1999) related shock absorbency to the stiffness of a shockpad, by stating a stiffer pitch will provide less cushioning (shock absorbency) than a compliant pitch and this can be associated with overuse injuries, however no data was provided. Conversely, Bartlett (1999) identified excessively compliant pitches promoting injury though fatigue. Stiffness and compliance are a measure of the force-deflection gradient created during an impact. Stiffer shockpads have a higher ratio of force to deflection and are therefore described as being less shock absorbent. With the exception of Young (2006), no other published research investigating the effect of shockpad design on shock absorbency could be found.

Resilience is second property of a pitch system attributed to the shockpad layer, which influences player and ball interactions and safety. Watson (1986) defines resilience as the ratio of returned energy after an impact to that put in during the impact. For player interactions, a lack of resilience can cause fatigue, predisposing to injury (Bartlett, 1999), but too higher level can again cause injury (Watson, 1986). Rebound resilience also is also important for ball interactions. The higher the resilience, the higher a ball rebounds (Watson, 1986). Young (2006) is the only researcher found to examine the effect of shockpad design on ball interaction characteristics. He measured a 5 cm hockey ball rebound height increase by increasing shockpad thickness from 6 to 20 cm. Published data for resilience of changes due to shockpad design for player interactions could not be found.

The shockpad layer is expected to exhibit durability against mechanical loading and environmental conditions throughout its service life. Outdoor sports pitches are subjected to numerous environmental conditions, particularly variations in heat and moisture. A shockpad is required to possess sufficient porosity to drain large quantities of moisture (FIH, 1999) and to resist degradation by this media. There should also be no marked changes in the playing characteristics exhibited by a shockpad due to constituent materials or construction quality over the range of standard service temperatures. Dimensional stability of a shockpad under loading and changing environmental conditions is also a requirement to prevent ridges and seams being formed in the surfacing layers (Tipp and Watson, 1983).

Shockpad Design

There have been numerous designs for shockpads over the years, many of which are still commercially available today. The most popular type used in Britain is the cast in-situ variety. This shockpad is composed of recycled rubber particulate in a polyurethane binder (Tipp and Watson, 1982; Fleming et al, 2002). The constituent components are combined, laid and compacted on site. The mix design, thickness and compaction levels are thought to determine ball and player interaction characteristics (Tipp and Watson, 1982).

Prefabricated shockpads are very similar in design and behavioural characteristics to the cast in-situ variety, however they are manufactured in a controlled factory environment. They can be cast into a variety of shapes and profiles, although sheets are preferred over tiles for sports pitch applications as there are fewer seams that cause inconsistencies (Tipp and Watson, 1982). Prefabricated shockpads are rolled out on site and adhesively bonded to the base.

Integral shockpads are manufactured to be integrated to the underside of synthetic turf. They are generally constructed from a foamed polymer and designs are significantly different to bound rubber particulate shockpads. The level of cushioning they provide can be varied by altering their thickness or by using them in combination with a cast in-situ or prefabricated shockpad.

Each shockpad type has both merits and drawbacks. Cast in-situ shockpads are laid in sections and joined to remove seams. They can be laid to any desired thickness, correcting minor thickness variations of the foundation layer (Watson and Tipp, 1987). The major disadvantages of cast in-situ shockpads are the increased potential for property and thickness variations due to constructors experience and variable climatic conditions during cure (as detailed in Section 2.3.1). The controlled manufacturing environment for prefabricated and integral shockpads reduces the potential for property variations due to changing climatic conditions. However, as they can only be manufactured in single sheets over a limited range of thicknesses; therefore seams and ridges can be created in the pitch through shrinkage or expansion. The incorporation of the shockpad with the synthetic carpet for integral shockpads reduces the likelihood of ridges occurring, however it is required to be replaced at the same time as the carpet. The carpet lifetime depends on the amount of use a pitch receives, however this is generally 7 years (Fleming et al, 2002). Cast in-situ and prefabricated shockpads may last two carpet lifetimes.

2.2.1.3 Carpet Layer

It is the role of the carpet layer to interact with the shockpad to produce the required ball and player interactions and to create friction to produce correct roll pace and distance across the pitch surface. Synthetic carpets are typically specified by the polymer used to form the carpet pile fibres, carpet pile height and density and materials used within with carpet pile. A range of synthetic carpets specified for different sports are described in Table 2.1.

Multi-use games areas (MUGA) allow a range of different sports such as hockey, football and tennis to be played and are commonly installed at schools. Traditionally these pitches used short pile sand filled or sand dressed carpets such as those shown in Table 2.1, but recently there has been a trend towards short pile rubber in-filled carpets to reduce friction burns caused by players falling. The ball and player interaction characteristics of MUGA carpet systems are not engineered for specific sports (Crawshaw, 1999) and are also not suitable for high level competitions (e.g. for hockey; FIH, 1999).

Third generation carpet systems are specialist systems used specifically for football and rugby. These systems typically employ long carpet pile with a deep sand and rubber in-fill for traction of footwear studs, to increase shock absorbency for player interactions and for player safety during falls. The long carpet pile and rubber in-fill would increase ball roll friction and are therefore not suitable for hockey or tennis. In-filled artificial turfs are subject to compactions of the rubber and sand in-fill, reducing their shock absorbency and resilience abilities. Regular refurbishment is therefore required to ensure consistent properties (UEFA, 2003).

Carpets specifically for hockey, particularly at high standards, are typically water based. Water based carpets are classified by their short carpet pile and use a fixed watering system to wet the carpet. The surface is watered to reduce surface friction to increase ball pace and reduce injury to players. Water based carpets are not as suitable for football and rugby due to high surface pace of the ball and high ball rebound height.

2.2.2 Loading of Synthetic Sports Pitches

Construction equipment, maintenance vehicles, players and balls are the main source of loading applied to sports pitches. The construction of foundation layers (sub-base and tarmacadam) requires the use of rollers to compact and level the surface. Shockpads typically employ a tractor and a small-scale paving machine (further detail in Section 2.3.1) during construction. Rubber and sand in-fill placed on the carpet layer is brushed into the carpet pile using a quad-bike sized vehicle, which is also used periodically as a pitch maintenance vehicle. These construction and maintenance vehicles typically apply a combination of compressive and shear stresses (Fleming et al, 2002). However, the magnitude of these stresses and their potential to damage the pitch is not well documented in literature. While the stresses applied by maintenance vehicles are expected to be significantly higher than stresses (and loads) applied by players and balls, they are applied much less frequently.

The most frequent source of loading of sports pitches post-construction is applied by players and balls. A vast quantity of published literature examining the forces generated during player-surface interactions exists (For example, Mc Mahon and Green, 1979; Nigg et al, 1984; Nigg, Cole, and Bruggemann, 1995; Wilson, Rochelle, R.D. and Bischoff 1997; Ozguven and Berne, 1988; Munro, Miller and Fuglevand 1987; Cavanagh and Lafortune, 1980), however very few of these interactions were measured on synthetic sports pitches. The majority of these player-surface interaction tests were conducted by experimental measurements of impact forces obtained by human subjects impacting a force plate. The force plate provides an output of 'vertical ground reaction force' against contact time and is a measure of the vertical force component acting on the player. Forces acting in the horizontal lateral-medial and fore–aft directions can also be measured by the force plate, but are considered by many researchers to be less significant in producing impact injuries and are there often not published. Horizontal forces are considered more significant for the carpet layer as most horizontal movements will be accommodated by movement of the carpet pile and in-fill materials than the shockpad layer, where only larger forces will be transmitted.

Force plate data may contain noise which is required to be filtered before analysis. As noise is typically high frequency and useful data relatively low frequency, a Butterworth Low pass filter is often applied to remove this noise and retain data demonstrated, for example, by Winter (1980).

The ground reaction force for a typical human interaction with a force plate using a heel-toe running style in a straight line is shown in Figure 2.3. The first peak in load is attributed to the heel strike which generally occurs within the first 50 msec of contact. It is termed the 'impact' peak; it is characterised by high rates of loading and was used to develop the Berlin Artificial Athlete test of simulating player impacts on sports surfaces. The second peak is due to the push-off from the toe and is similar in magnitude to the impact peak but has a much slower rate of load application.

A small number of publications were also found that focus on player-surface interactions for sporting movements other than running. These movements include jumping (Ozguven and Berne, 1988; Adrian and Xu, 1990), walking, pivoting dodging, veering, lunging and cutting (Adrian and Xu, 1990). The peak vertical and horizontal forces measured for these sporting movements are compared to data for heel-toe running measurements of other researchers in Table 2.2.

Vertical impact forces where shown to always be higher than horizontal forces with the exception of a stopping movement. Player interactions are therefore shear forces with a large vertical component. Munro et al (1987) showed running velocity to have an effect on peak impact forces and a comparison of results for a running velocity of 3 m/sec with Nigg and Yeadon (1987) showed the running surface to also affect peak impact forces. Contact time was seen to vary widely according to the type of movement with walking showing the longest contact time of 1.1 sec and the 45°

cutting movement by Blackburn et al (2005) for the 3rd generation pitch showing the shortest contact time of 0.225 sec. Research into player movement using GPS tracking, summarised in Table 2.3, shows standing, walking and jogging to be the predominant movements of players during hockey. For walking and slow running, peak impact forces generally ranged from 1.3 to 1.6 times body weight (BW), which for a player with a body weight of 90 kg relates to a peak impact force ranging from 1170 to 1440 N.

In contrast to the vast quantity of research published measuring the effect of the surface on the player, McMahon and Green (1979) examine the forces applied to surfaces by players. Their research led to the development of a mathematical relationship to describe average vertical force applied to a surface by a person running, and is given by Equation 2.1. This work to investigate the influence of track stiffness on running showed practical measurements agreed quite well with their theoretical predictions. However, these measurements were only conducted for two surfaces of different stiffness (very stiff and very compliant). Their model predicts average force over the contact time, therefore providing a quantity to compare average force values for different surfaces, but it is limited in predicting peak forces or demonstrating the force-time relationship during surface loading and unloading.

$$\overline{F} = m_m g + \frac{2 m_m v}{t_c} \qquad \text{---------- Equation 2.1}$$

Where:

$\overline{F}$	=	Average Force	[N]
m_m	=	Athlete Mass	[kg]
g	=	Gravity	[m/sec^2]
v	=	Impact Velocity	[m/sec]
t_c	=	Contact time	[sec]

Little research could be found that investigated the magnitude of forces transferred to each layer of a synthetic pitch and their subsequent behaviour. The majority of player-surface research was conducted on rigid force plates and did not consider force reductions that could occur by changing the design of synthetic surfaces. Also, no published literature could be found to quantify impact forces generated by balls. Player-surface interactions are of more interest due to the injury prevention aspect of this research; however this is not the case for ball interactions which are more concerned with energy return than the peak forces generated.

2.2.3 Mechanical Degradation

Synthetic sports pitches are subject to mechanical degradation by loading cycles applied by players and balls. The extent of mechanical degradation of a pitch will be dependent on factors such as average player mass, type of movements (e.g. jumping or cutting), pitch usage and maintenance.

The magnitude of loads applied during different types of sporting movements was reviewed in detail in Section 2.2.2. The magnitude of vertical loading was shown to range from 1.5 BW for a player walking up to 5.7 BW during a jump; however typical loads for running were shown to range from 1440 to 2250 N for a 90 kg player. The loads applied to the pitch therefore depend on player mass and the specific sports played on the pitch. Rugby generally has heavier players than hockey and football with a mass of around 90 kg for amateur players (Gabbett, 2000). Many sporting movements are common to sports played on synthetic pitches, such as cutting and veering, but other movements such as jumping are more likely in football than rugby and hockey. Research using GPS tracking of players for hockey is summarised in Table 2.3. The research shows the majority of loading applied to pitch by players is by standing and walking, followed by jogging. An average of 92% of a player's time is spent standing, walking or jogging during a game of hockey.

The hours of use a pitch receives varies widely amongst pitches. Synthetic football pitches built with assistance from the Football Foundation (UK) requires them to be available for use for a minimum of 85 hours per week (Football Foundation, 2004). Young (2006) outlines the usage of six water based hockey pitches in UK being used between 50 and 75 hrs per week. Maintenance is recommended to be carried out regularly, however no published information regarding maintenance schedules or procedures could be found.

The system of play through the centre of the pitch, through the wings and grouping of players at the goal mouth may lead to higher mechanical degradation in certain areas of the pitch. Techniques of player tracking with synchronised GPS and video have been developed to determine distance covered by players during a game and the velocity and time of movements (Figueroa et al, 2005; Petersen et al, 2004; Spencer et al, 2004). However, only Figueroa et al (2005) graphically showed movement of a player across a football pitch. The movement of the player, of unspecified playing position, across a pitch is shown in Figure 2.4. The centre section of the pitch shows more use than the wings of the pitch for this player, however the movements of the whole team are required to accurately assess high use areas of the pitch as playing position may affect sections of the pitch used by certain players.

The change in mechanical properties of water based hockey pitches due to degradation was investigated by Young (2006). Over a period of three years, Young (2006) visited six water based hockey pitches to conduct mechanical property testing. The Berlin Artificial Athlete test, detailed in Section 2.2.5, is a test used to measure the peak impact force of a synthetic sports pitch under a simulated player dynamic load compared with peak impact force of the device on a rigid surface, giving the mechanical property of force reduction. Over the three year period, Berlin Artificial Athlete tests were conducted on 25 test locations on each pitch, results are shown in Figure 2.5. All six pitches showed decreasing force reduction over the three year period, indicating decreasing shock absorbency with age. Changes in mechanical properties are due to degradation of the pitch, which includes carpet and shockpad wear; however the overall effect of degradation due to degradation of each layer is not investigated or how mechanical properties changes indicating high use areas of the pitch. These changes in mechanical properties are from a combination of mechanical and environmental degradation. Environmental degradation is reviewed in the following section.

2.2.4 Environmental Degradation

The outdoor environment of synthetic sports pitches subjects them to varying climatic conditions. Some conditions that must be considered when designing pitches are listed in Table 2.4, together with typical problems they cause.

Synthetic sports pitches are subject to degradation by moisture, oxygen and ultraviolet light. The carpet layer of the synthetic pitch is subjected to all three degradative agents, requiring the addition of stabilisers during manufacture to prevent excessive degradation over its service life. Shockpad and foundation layers are covered by the carpet layer and therefore protect them from ultraviolet light, but their porous structure makes them liable to degradation by moisture and oxygen. Cast in-situ and prefabricated shockpads contain a polyurethane binder that coats the rubber particulate.

Synthetic pitches are subject to large temperature variations. Williams (2006) found the temperature of the carpet layer of a synthetic pitch varied between 13 and 82 °C over a 12 hour period for pitches located in the Utah, USA during late spring. No data measuring the temperature variation of pitches in the UK could be found. The mechanical properties of elastomers, such as those used in the shockpad layers of a synthetic sports pitch, are temperature dependent (Nagdi, 1993). Large temperature variations in pitch layers can cause contraction and expansion, forming ridges or gaps in the pitch, which will affect the playing performance of the pitch. Large variations in temperature may also produce differing pitch performance characteristics (Tipp and Watson, 1982).

2.2.5 Standard Test Procedures

Many sources outline test procedures and performance criteria to ensure a level of quality in sports pitches being constructed. These procedures were developed to ensure the properties of whole pitch construction in terms of player and ball interaction characteristics, safety and durability fall within acceptable levels of performance.

A general set of British Standards, designated BS 7044, were developed to outline common test methods used for synthetic sports pitches, but do not specify typical values for ball and player interaction characteristics, safety or durability for specific sports. A European standard is currently under development to replace the British Standard.

More specific test procedures for outdoor sports pitches are outlined in documents produced by relevant sporting governing bodies for certification of newly constructed pitches. Performance requirements for certification of hockey pitches are stipulated by the International Hockey Federation (FIH) in their publication titled 'Synthetic Hockey Pitches: Handbook of Performance Requirements' (1999) and rugby pitch performance requirements are stipulated by the International Rugby Board (IRB) in their publication 'Performance Specification for Artificial Surfaces for Rugby' (2005). Football pitch specifications are governed at different levels by different organisations. The Football Association (FA) govern pitches to be used at community levels with their publication titled 'Guideline Performance Standards for Outdoor Artificial Grass Pitches for Community Use' (2005), while the United European Football Association (UEFA) stipulate standards for European standard pitches with their publication titled 'Artificial Turf Requirements and Recommendations' (2003). Fédération Internationale de Football Association (FIFA) also stipulate test methods for world class synthetic football pitches in their publication 'FIFA Quality Concept: Handbook of Test Methods and Requirements for Artificial Turf Football Surfaces' (2005)

Synthetic pitches for football and hockey can be certified to accommodate different levels of competition. FIFA (2005) and FIH (1999) performance requirements stipulate tighter performance criteria for higher level competition pitches. FIFA uses a one and two star performance rating and the FIH uses a 'global', 'standard' and 'starter' rating to grade pitches. These performance limits stipulated by sporting governing bodies are developed through 'in-house' testing. There is no data outlining the type and number of pitches tested, whether they are actual pitch constructions or pitch samples testing in the laboratory or justification of how appropriate specifications for player and ball interaction characteristics were determined for each sport. The absence of this published data makes it difficult to critically assess the performance specifications issued by sports governing bodies.

Some common tests procedures stipulated by these sporting governing bodies and their performance criteria for various competition levels are reviewed in the following sections. Tests specified for player and ball interaction characteristics are examined individually and a summary of performance specifications for hockey, rugby and football provided in Table 2.5.

2.2.5.1 Player-Surface Interaction Tests

The most widely specified tests to determine shock absorbency related player interaction characteristics of a synthetic pitch are 'artificial athletes'. Artificial athlete tests were developed in 1976 in Germany as a shock absorbency test that could be conducted on sports surfaces in-situ (Kolitzus, 2000). These mechanical tests are used to gain repeatable and comparable measurements of surface shock absorption.

Two different apparatus were developed for these tests, the Artificial Athlete Stuttgart and the Artificial Athlete Berlin, the specifications for each given in Table 2.6. Both tests were developed to simulate the heel of a player impacting the surface in the vertical direction only, by producing a controlled load rate and appropriate impact energy. The Artificial Athlete Stuttgart (AAS) uses deflection transducers to measure the vertical deflection of a surface under load of 0.5 kN. Higher deflection measurements relate to a more compliant pitch during player interactions. The Artificial Athlete Berlin (AAB) applies 0.2 kN load to determine a peak impact force to a stiffer spring, providing a more rapid contact time. A test is conducted on a rigid surface such as concrete and then a second test is conducted on the sports pitch. The difference in peak impact force measured for the concrete surface and synthetic pitch is termed 'force reduction' and is determined using Equation 2.2. Higher force reduction measurements show increased shock absorbency of the synthetic pitch.

$$F.R = \left(\frac{F_r - F_S}{F_r}\right)\times 100 \quad \text{---------} \quad \text{Equation 2.2}$$

Where:

F.R	=	Force Reduction	[%]
F_r	=	Impact force on rigid surface	[N]
F_s	=	Impact force measured on synthetic pitch	[N]

Investigations into the accuracy of these tests claim that the AAB reproduces the general force pattern of a player impacting a surface during heel-toe running (Kolitzus, 2000) but suggestions are made by Dixon, Batt and Collop (1999) that this device may not be appropriate for simulating human interactions. Other drawbacks of this test are that it is cumbersome and heavy, making it difficult to transport around the pitch.

Force reduction and deflection values specified by FIFA, FIH and the IRB in their publications for performance requirements of synthetic pitches are given in Table 2.5. Lower standard synthetic pitches, such as the starter hockey pitch and one star football pitch, allow greater range of force reduction and deflection (FIFA only). The range of acceptable performance is reduced for higher standard global hockey pitches and two star football pitches. The reduced range of force reduction and deflection provides increased consistency of player interaction characteristics among higher standard pitches.

The 2.25 kg Clegg Hammer is suggested by Fleming et al (2004) to be a suitable alternative test to the AAB, due to it being light, rapid and portable. The Clegg Hammer was originally developed by Dr. Baden Clegg as a test for measuring the mechanical properties of soils. It employs a 2.25 kg mass with an integrated accelerometer, dropped from a height of 45 cm through a guidance tube. The accelerometer records peak deceleration of the mass and outputs it to a screen in units of gravities. The suitability of test was assessed by Young (2006) by using a Clegg Hammer in conjunction with AAB to test the shock absorbency of water based hockey pitches. A good correlation was shown between measurements of the two devices which was attributed to a similar input energy, however the Clegg Hammer did have a shorter contact time than the AAB.

The Head Impact Criterion (HIC) is an additional player-surface interaction test to prevent head injuries during falls. The test method described in the standard BS EN 1177:1998 uses a hemispherical head 160 mm in diameter, with an attached accelerometer, to be dropped from various heights to create a graph of acceleration-time graph. The HIC for each drop height is calculated using Equation 2.3 and a graph of HIC-drop height is created. The drop height corresponding to a HIC of 1000 is referred to as the 'critical fall height'. This test is only specified by the IRB, where a critical fall height of greater than 1.0 m is specified.

$$HIC = \left[\left(\frac{\int_{t_1}^{t_2} a.dt}{t_2 - t_1} \right)^{2.5} \times (t_2 - t_1) \right] \quad \text{--------- Equation 2.3}$$

Where:

HIC	=	Head Impact Criterion	
a	=	Acceleration	[m/sec^2]
t_1	=	Initial Time at Impact	[sec]
t_2	=	Final Time at Impact	[sec]

The critical fall height, corresponding to a HIC of 1000, represents a threshold above which risk of fatal or severe head injury is unacceptable (Shorten and Himmelsbach, 2002). Their specification however, for a critical fall height to be above 1 metre appears low, particularly for rugby players lifted around 3 metres from the ground during line-outs. There is no justification provided by the IRB (2005) for how this lower limit of 1 metre was determined. However, Shorten and Himmelsbach (2002) identify shock absorption and maximum deflection of the surface as influencing factors in HIC values and suggest that accommodating high critical fall heights may produce ball rebound and player interactions that make the pitch unplayable.

Friction tests are used to measure player-surface interactions with the carpet layer and in-fill. Slip resistance is measured using a Modified Le Roux Pendulum Tester, which uses a test foot to swing across the face of the carpet and measure the energy lost in the interaction given in units of μ. Rotational friction is a measure of the ability of a player to quickly change direction. A Rotational Traction apparatus measures the amount of torque required to start the motion of a studded shoe against the synthetic pitch. The specification limits are placed to prevent players slipping on low friction surfaces and preventing joint and ligament injuries on high friction surfaces (IRB, 2005).

Linear friction tests were deemed useful in providing an index for the frictional characterises of synthetic pitches; however, they are not considered suitable in representing 'real' human movement as normal forces and movement speeds are much lower than those generated by players (Dixon et al, 1999). Also, rotational friction has been shown to be influenced by carpet materials, normal force, speed of movement and contact area (Valiant, 1987 and 1990). The test is not capable of simulating the variety of horizontal movements used by players on synthetic pitches, but again does act as an indexing test to compare rotational friction measurements among pitches.

2.2.5.2 Ball-Surface Interaction Tests

The ball interaction properties of a synthetic pitch are required to be measured to ensure uniform and appropriate ball-surface interaction characteristics are displayed across a pitch. The two most common tests used to simulate ball interactions on synthetic pitches are ball rebound and ball roll tests.

Ball rebound tests measure the height a ball will rebound to when dropped from a specific vertical height. The test involves a ball (suited to the intended sport) being dropped from a specified height and the rebound height of the ball is measured. FIFA tests for football use a drop height of 2m and require a rebound height of 0.60 to 1m for a one star pitch and 0.60 to 0.85m for a two star pitch (FIFA, 2005). FIH testing procedures use a drop height of 1.5m and require a rebound height of 0.1 to 0.4m for a starter pitch, 0.1 to 0.3m for a standard pitch and 0.1 to 0.25m for a global pitch (FIH, 1999). Test procedures for rugby use a round ball (due to the random bounce produced by rugby balls) to achieve a 30 to 50% rebound height (as a percentage of drop height) (IRB, 2006), however the required drop height is not specified.

Ball roll tests are used to determine the friction of the carpet by measuring the distance a ball will travel along the surface for a given energy input. Energy is given to the ball by rolling it down a ramp of specified incline onto the surface and the distance from the end of the ramp to the stationary ball is measured. Tests for football require a roll distance of 4 to 10m for a one star pitch and 4 to 8m for a two star pitch (FIFA, 2005). Hockey ball roll tests require 5 to 20m roll distances for a starter pitch, 5 to 15m for a standard pitch and 9 to 15m for a global pitch. Again, tighter specifications are given for higher level football and hockey pitches to reduce property variation across the pitch. Ball roll tests are not conducted for rugby as the ball does not roll across the surface during play.

2.3 Cast In-situ Shockpads

The design and functional requirements of shockpad layers of synthetic sports pitches were briefly discussed in Section 2.2.1.2. The role of the shockpad layer is to interact with the carpet to provide appropriate levels of shock absorbency and resilience for player and ball interaction characteristics and it must be designed to resist mechanical and environmental degradation to ensure it performs its function throughout its service life.

Three common shockpad types, cast in-situ, prefabricated and integral were identified. This section details the construction, constituent materials, the effect of mix design on mechanical properties and general test methods for shockpad layers and constituent materials. The prefabricated shockpad is similar to the cast in-situ shockpad in terms of constituent materials, mix design and test methods for quality control and therefore most of the information (with the exception of construction methods) is also relevant to prefabricated shockpads. From this point, the term shockpad will refer to the cast in-situ variety (and in most case will also be relevant to the prefabricated variety) unless otherwise stated.

2.3.1 Construction

Details outlining the processes involved in the construction and curing of cast in-situ shockpads contained in this section were obtained from a publication by Tipp and Watson (1982) and through observations made during visits to synthetic pitch construction sites. No further published sources could be found that describe the construction process or identify possible sources of variation in construction process or curing conditions that may affect the final properties of the shockpad. Specifications for shockpads by sports governing bodies stipulate the quality requirements of the final product but do not state how the constructors are required to achieve them. Though observation it appears the quality of the shockpads produced is reliant on the knowledge and training given to the construction crew.

The process of shockpad construction was observed during site visits during the period of 2003-2004 to gain an understanding of the construction methods as they were not widely published in literature. During these site visits, it was observed rubber particulate was supplied in 25 kg bags which were directly placed into the mixer. Polyurethane binder was poured into a bucket from a large container up to a line which indicated the correct ratio for each bag of rubber and the binder was poured into the mixer. The binder was a viscous fluid, therefore a significant quality settled in the bucket after the bulk had been poured into the mixer. Viscosity of a liquid is temperature dependent; therefore the quantity remaining in the bucket would vary with air temperature. The mixer operative stated that the remaining binder in the bucket was accounted for 'by adding extra binder on cold days', but there appeared to be no data to base extra binder requirements on according to temperature.

A standard mixing time of three minutes was used by this particular construction company. No published data could be found that examined the properties of shockpads according to mixing time, and it is unknown if any study is conducted by shockpad constructors. The mix was transferred from the mixer to a small dump truck and transported to the appropriate section of the pitch to be laid. The standard mixing time did not appear to be strictly adhered to by the construction crew, with mixing time being judged by the time it took the dump truck to dispose of a load and return. Mixing times for shockpad laid near the mixer were approximately half the standard mixing time.

Batches of the rubber-binder mix were placed along the length of the pitch and were compacted into a level shockpad layer in strips using an oscillating levelling beam (Figure 2.6). Adjacent strips of shockpads were joined using a paving trowel to form a continuous layer. Shockpad thickness was determined by the adjustable height of the levelling beam, with height variations in the foundation layer accounted for by flat levelling beam, producing variations in shockpad thickness. The compaction levels of the oscillating levelling beam also produced a porous shockpad to allow for drainage of the surface water through the pitch structure.

The air temperature and humidity determine the rate at which the polyurethane binder will cure. One polyurethane manufacturer suggests that optimum conditions are 25°C and 50% relative humidity (Peel, 2000). Excessive temperature and/or humidity above the optimum level can hasten curing, reducing the mix workability, and thus making the shockpad more difficult to lay. Conversely, low temperature and humidity will lengthen the time required for cure, however some installers have overcome this problem by spraying the surface with water or adding water to the rubber-binder mix before compacting (Tipp and Watson, 1982). No published data could be found quantifying the cure time of a shockpads and how this is affected by environmental conditions or data outlining the effect of cure conditions on the mechanical properties of the shockpads.

Overall, observations made during site visits suggest possible variations in binder content across the shockpad and also locally due to poor mixing. Tipp and Watson (1982) show the effect of incorrect mixing and inadequate compaction on tensile properties in Table 2.7. The control sample represents the properties of a shockpad with the correct proportions of rubber and binder and standard construction procedures are followed. Samples taken from two sites, A and B, show the specifications of the control sample are poorly met.

Thickness of the site samples were considerably less than the control samples, with thickness on Site B 5.5 mm less than specified in places. Similarly, poor compaction represented by reduced mass/unit area and density measurements of the site samples compared to the control samples show poor site practice. The reduced thickness and compaction levels of site samples A and B result in only 20 and 17% (average) of the control tensile strength and 60 and 43% (average) of elongation at break being achieved respectively. Tipp and Watson (1982) further identify compaction levels as having a direct effect on shockpad stiffness and excessive levels of compaction can lead to an uneven or cracked surface as the shockpad ages. Cracking may occur between adjacent strips if joints are not made correctly. There is no data provided in their publication to quantify 'excessive' or demonstrate the relationship between compaction and stiffness.

2.3.2 Standard Test Procedures for Shockpads

Sporting governing bodies stipulate tests to be conducted on shockpads post-construction to ensure they meet design specifications and performance standards. UEFA (2003), FIFA (2005), FA (2005) and IRB (2005) provide test method requirements for shockpad layers of football and rugby pitches, however the FIH (1999) do not require any shockpad testing for hockey pitches. An outline of these stipulated design verification and performance tests for synthetic football and rugby pitches and specifications for acceptable ranges for test measurements are provided in Table 2.8.

Mass per unit area and thickness measurements are stipulated to verify the design specifications of the shockpad are met. Mass per unit area is a measurement of rubber particle compaction within the shockpad (similar to bulk density) and is stipulated by UEFA, FIFA, FA and IRB. UEFA is the only governing body to set limits of 1 to 25 kg/m^2. These mass per unit area limits set by UEFA set bulk density requirements for a 12 mm shockpad to be between 83 kg/m^3 and 2083 kg/m^3. The bulk density of 2 to 6 mm sized rubber particulate is 470 kg/m^3 (Charles Lawrence PLC, 2003) uncompacted and the density of recycled rubber particulate (i.e. the maximum density a shockpad could be compacted to by removing all voids) is between 1120 and 1150 kg/m^3 (Manuel and Dierkes, 1997). These limits placed by UEFA are therefore too wide to distinguish poorly constructed shockpads as the lower limit is below the bulk density of un-compacted shockpads and upper limit twice the achievable bulk density. UEFA and the FA also require shockpad thickness measurements to be specified. Shockpad thickness varies according to pitch design, however no tolerance for acceptable variations from the specified thickness are stipulated by any sporting governing body.

Tensile strength, force reduction and compressive modulus are specified to determine the performance characteristics of shockpads. Tensile strength of shockpads, determined according to the standard method described in EN 12230, is measured by dividing the load to failure by the cross sectional area of the sample. Tensile strength measurements are required by UEFA and FIFA for shockpads in football pitches, however only FIFA specifies a minimum value of 0.15 MPa. This minimum strength criterion has been adapted from the IAAF standards for certification of athletics tracks (IAAF, 2003). However, athletics tracks generally employ smaller rubber sizes, higher binder contents and a much denser structure than shockpads and would therefore inherently have a higher tensile strength.

The compressive modulus of shockpads is required to be measured by FIFA and the IRB, however there are no limits placed on performance by either governing body. The test is a measurement of compressive stiffness, however the test method BS EN ISO 604:2003 is specified for rigid plastics which exhibit a linear modulus; shockpads exhibit a non linear modulus, requiring an average modulus to be determined. It is conducted at a speed of 1 mm/min, which does not represent the behaviour during dynamic impacts from players and balls, as detailed in Section 2.2.2.

UEFA are the only governing body to specify force reduction measurement by an artificial athlete. The test used to measure peak impact force reduction for whole pitch constructions is detailed in Section 2.2.5.1. Wide limits of 20-70% force reduction for shockpad layers are considered acceptable, which would only eliminate the very rigid or very compliant shockpad constructions.

The design verification and performance tests stipulated by sporting governing bodies for shockpads are only required to be conducted if the whole pitch is to be certified for certain levels of competition. Synthetic pitches installed at schools or for community use are only required to meet design and performance standards contained in the construction contract. Sport England (2003) states that contracts should include specifications for rubber type, binder type, binder content and shockpad thickness and that construction quality could be judged by samples fulfilling a minimum tensile strength criterion of 0.1 MPa. Sport England does not provide guidance for suitable constituent materials or acceptable tolerances for variation in binder content or shockpad thickness, or specify performance tests to determine if suitable safety, durability and ball and player interaction characteristics are exhibited by the pitch.

Testing of shockpads post-construction is specified for two reasons; design verification and performance standards. The design and construction of shockpads for football, hockey and rugby were shown to be very similar, however the range of tests stipulated by sporting governing bodies varied. The tests specified by governing bodies suggest they know these factors to be important for shockpad quality and performance, however they place very wide tolerances for shockpad layers. Design is verified by two methods, mass per unit area and thickness, however in the construction of shockpads many possible variations were identified in the constituent materials, binder content, binder distribution, compaction levels and curing conditions. Shockpad performance was specified in terms of tensile strength, force reduction and compressive modulus; ball interactions were not considered and no reasonable tolerances were placed on performance. This lack of comprehensive test procedures and specification of acceptable tolerances for shockpad layers to verify design and measure performance in safety, durability and player and ball interaction performance suggests little previous research has been conducted on shockpad layers into the effects of shockpad design or behaviour.

2.3.3 Recycled Rubber Particulate

Rubber particulate is the major constituent of cast in-situ shockpads. The functional requirement of shockpads to demonstrate shock absorbency and resilience is fulfilled by the mechanical properties of the rubber used to construct it. The shock absorbency and resilience it exhibits has made polyurethane bound rubber particulate useful for applications such as athletics tracks, playground safety surfaces and walkways. The type of rubber particulate used varies depending of the application; athletics tracks and walkways are often Ethylene-Propylene-Diene Monomer (EPDM) rubber as it is available in a range of colours. Shockpads are situated below the carpet layer of synthetic pitch, therefore colour is not important, and rubber particulate derived from the granulation of post-consumer car tyres is specified for most shockpad installations. This section reviews the properties of rubber that make it suitable for use in shockpads, the composition and mechanical and physical properties of rubber particulate, the process used to reduce tyres to produce particulate and methods used to control the quality of recycled rubber particulate.

2.3.3.1 Composition

The rubber used to construct shockpads is generally obtained from the granulation of post-consumer tyres. Tyres can be sourced from numerous vehicles, however shockpad particulate is generally limited to those from trucks and other heavy-duty vehicles. The limitation on suitable tyres is due to the high fibre content of car tyres being difficult to remove during processing and when bound, significant quantities of polyurethane binder can be absorbed by the fibre reducing the binder content available for bonding rubber particles.

The bulk of a truck tyre is constructed from rubber compounds, with steel belting and fibres added for strength and shape retention. The steel content of truck tyres varies according to manufacturer design. Background provided in prEN 14243 and Kumho (2005) agree the steel content of a truck tyre by mass is approximately 25%, however Continental Tyres (1999) suggests this can be as high as 33%. A cross sectional view of a tyre, Figure 2.7, shows the distinct sections of steel and rubber. The rubber section is made up smaller sections of rubber with varying composition. Tread and sidewall cover the outermost sections of the tyre and the inner liner covers the inner section of tyre. Large sections of rubber are also contained in the apex sections of the tyre which act to stiffen the sidewall and prevent sideways movement of the tyre (Kumho, 2005). Smaller sections of rubber are contained in the gum chafer and a coating of the wires to promote adhesion between the steel and other rubber sections (Bennett, 2005).

Rubber compounds used to construct each section are composed from a complex blend of various rubber types, fillers and additives. Tyre sections often contain a blend of rubbers to optimise their performance. Blends contain a mixture of various elastomers, dispersed on a microscopic level, but do not contain any strong chemical bonding between different chains. Additives are also included in rubber to improve its properties and processability. Carbon Black is added to increase strength and stiffness of the compound, which also inherently stabilises the compound to ultraviolet radiation effects. In addition, antioxidants are used to slow down thermo-oxidative degradation, with processing aids, accelerators and sulphur added to ease manufacture and produce cross-links during vulcanisation. The type of rubbers and the proportion of additives and fillers for each tyre section vary depending on tyre manufacturer; making characterisation of the particulate produced from these tyres a difficult task.

Tyre manufacturers do not publish details of their products for commercial reasons. Publications detailing tyre composition by French (1989) and Barbin and Rodgers (1994) and communications with tyre manufactures (Kumho, 2005; Bennett, 2005) provided a general description of the rubber types used in different tyre sections; however the proportion of rubber to fillers and other additives contain in the rubber compounds could not be found.

The composition of the tread section of the tyre is the most published of the tyre sections as it plays a crucial role in the performance and lifespan of the tyre. Natural rubber is identified as the base rubber used for tread sections of new tyres (French, 1989), which may be blended with Polybutadiene Rubber (BR) in proportions between 25 and 30% (Bennett, 2005). Retreads for truck tyres can contain up to 60% Styrene-Butadiene rubber (SBR) for ease of manufacture and cost reduction (Bennett, 2005). The sidewall sections of truck tyres typically contain a blend of NR and BR (Kumho, 2005) typically in the proportion of 50% NR – 50% BR (Barbin and Rodgers, 1994; Bennett, 2005), but may also contain a small proportion of SBR. The inner lining of tyres is required to prevent permeation of air to maintain pressure. Butyl rubber or Halobutyl rubber (Kumho, 2005) is typically used for the inner liner section. The apex section may contain a blend of NR and SBR (Bennett, 2005). Compositions for smaller tyre sections, such as a coating applied to the steel wire to improve adhesion to rubber sections, are not widely published but have been identified as being predominantly NR (Kumho, 2005; Bennett, 2005).

Some researchers have attempted to analyse the composition of rubber particulate. Thermogravimetric Analysis (TGA) appears to be the most widely used analysis technique as it identifies the rubber hydrocarbon, filler (carbon black and inorganic) and extender oil content of a rubber compound. Fourier Transform Infrared

Spectroscopy (FTIR) may also be conducted in conjunction with TGA to confirm the type of rubber hydrocarbons present in the compound.

Forrest (2001) presents a review of the methods employed in FTIR and TGA. FTIR requires the pyrolysis of rubber samples to prevent interference from fillers and oils. The condensate obtained by pyrolysis is analysed by applying radiation of varying wavelength to the sample over the infrared spectrum. The proportion of energy transmitted through the sample for each wavenumber (inverse of wavelength) is recorded and output as a graph. A typical FTIR graph obtained for Natural Rubber is shown in Figure 2.8, where characteristic peaks occur at set wavenumbers to identify the rubber type. The technique is useful in providing a relatively quick identification of rubber types present but is inadequate for rubber compositional analysis alone as it does not identify filler or extender oil content.

TGA is conducted by placing rubber samples on a micro-mass balance and heating at a constant rate to around 800°C. The percentage mass loss with increasing temperature is recorded to produce the graph shown in Figure 2.9. Steps in the graph represent the decomposition of specific components of the rubber compound. Volatiles, such as extender oils and plasticisers, are the first components to decompose, followed by rubber hydrocarbons, carbon black and the remaining ash content represents inorganic fillers that do not decompose. The relative mass loss corresponding to each step in the graph is a measure of the mass of each component contained in the rubber sample. The derivative of TGA (DTGA) represents the rate of mass loss over the same temperature range and is also shown in Figure 2.9 superimposed on the TGA curve. The peaks that occur in the DTGA curve over the range of polymer hydrocarbon decomposition can be used in conjunction with FTIR results to identify the types of polymer used. This technique allows the analysis of small samples (e.g. 10 mg) in a short time; however different heating rates may shift the temperature of DTGA peaks making identification of polymer types difficult without FTIR data. For TGA analysis of NR, BR and SBR compounds used in truck tyres, NR decomposes first with a DTGA peak around 410 ±20°C and SBR and BR peaks overlap in the range of 470 – 490°C for heating rates of 30°C/min (Hull, 2005).

TGA data from the analysis of recycled rubber particulate is summarised in Table 2.9. The rubber particulate is from various sources that are not well described; however the composition does not appear to significantly vary. Ash contents appear to range from 3 to 5 %. Higher ash contents of 10-15% were measured by Bloxham (1962), however this may be due to compositional changes in tyres since this the research was conducted in 1962. Volatiles, representing extender oils and plasticisers, fall within the range of 10 -15 % for all researchers, with the exception of Cui (1999) who did not distinguish between volatile and rubber contents. Carbon black and rubber hydrocarbon content constitute the bulk of the rubber compound with values falling within close limits. Carbon black contents measured by Bloxham (1962) are lower than other researchers, which again may be a result of tyre compositional changes since this testing was conducted.

While rubber hydrocarbon, oil and filler content for rubber particulate sources were shown to fall within small bands, there was no identification of the proportions and types of rubber hydrocarbons present. Rouse (1997) performed FTIR analysis on a sample of rubber particulate, but did not identify the rubbers present. This combination of rubber hydrocarbon type, carbon black, volatile and ash content will influence physical and mechanical properties of the rubber particulate.

2.3.3.2 Physical and Mechanical Properties

When subjected to compressive loads, rubber exhibits behaviour similar to that shown in Figure 2.10. The different load and unload paths represent energy lost by conversion to heat. The phenomenon of energy loss is called hysteresis (Nagdi, 1993) and is calculated by the area contained within the load and unload curves called the hysteresis loop.

The linearity of the load and unload curves for force-deflection and stress-strain behaviour is dependent on the rate of strain (or rate of deformation or force) applied during compression. Song et al (2004) examined the effect of strain rate over a range of 0.0015 to 4700 sec^{-1} and demonstrated rubber became increasingly non-linear with increasing strain rate (Figure 2.11). Strain rates associated with peak impact force during player interactions are calculated to be in the region of 20 sec^{-1} based on 25 msec time to peak load (Dixon et al, 2000) and the assumption of a 50% strain within the shockpad (Walker, 1996). Based on the results of Song et al (2004), rubber contained in shockpads (neglecting the effect of the binder) would exhibit mostly linear behaviour at small strains (<60%), becoming slightly non-linear with at higher strains of around 60%.

There are many different types of rubber which demonstrate a variety of different physical and mechanical properties. The review of the composition of truck tyres, Section 2.3.3.1, showed Natural rubber, Styrene-Butadiene rubber (SBR) and Butadiene rubber (Bennett, 2005; Kumho, 2005) to be the predominant rubber types contained in recycled rubber particulate. A wide range of mechanical properties are quoted in literature for these rubber types, however the predominant force applied to shockpads by players and balls is vertically compressive, therefore this section will focus on compressive properties.

Resilience is a measure of the ability of a rubber to return energy. The standard test to measure the resilience of rubber differs from the ball rebound test used for whole synthetic pitch constructions as it uses a 0.35 kg mass attached to a pendulum. The pendulum is impacted into the rubber sample at velocity of 1.5 m/sec and the rebound velocity is measured using timing gates to determine resilience (Brown, 2006). Although the mass is higher than a typical hockey ball (0.16 kg), the energy input is lower due to the lower impact velocity; therefore being suitable as an indexing test to rank the rubber resilience but not represent ball and player interactions.

Hardness is defined as the resistance of the rubber surface to penetration by an indentor of specified dimensions to a specified load (Nagdi, 1993). Two different hardness measurements are commonly used, International Rubber Hardness Degrees (IHRD) and Shore Hardness Degrees, however both measurements are approximately equal (Nagdi, 1993). For perfectly elastic materials, hardness measurements are a directly proportional to Young's Modulus (also known as the Elastic Modulus) (Brown, 2006). The non linearity of rubber is shown in Figure 2.10 affects this relationship, however, data quantifying this effect could not be found in published literature. For this reason, hardness testing cannot be used to directly measure mechanical properties of rubber; however it remains a useful indexing test to distinguish property differences in rubbers.

The properties of hardness and resilience for NR, SBR and Butyl rubber are shown in Figure 2.12 and Figure 2.13 respectively. The mechanical and physical properties of these rubber compounds depend on the proportion of carbon black, plasticisers and sulphur added to the compound; this results in the wide range of values shown for each rubber type. As literature detailing the relative proportions of rubber to filler and additive content was not published the precise properties of each compound was difficult to ascertain.

The hardness of NR, SBR and Butyl rubber showed a similar range for three rubbers. The resilience of BR is similar that of NR (Nagdi, 1993) and NR and SBR showed high levels of resilience compared to Butyl rubber in Figure 2.13, and therefore higher energy return during impacts. Butyl rubber was shown in Section 2.3.3.1 to be contained in the inner liner section of a tyre only, which accounted for a low proportion of the rubber compared to the NR, BR and SBR rubber contained in the tread, sidewall and apex sections of the tyre, however exact proportions of each sections are not known.

The surface temperature for a pitch in Utah, USA was claimed to vary between 13 and 80°C from 7am to 7pm in late spring (Williams, 2006); temperature data for UK pitches could not be found. There was also no data of temperature measurements for the shockpad layer situated below the surface. The effect of temperature on the hardness and resilience of SBR rubber is shown in Figure 2.14. Over the range of -10 to 20°C (which may be considered likely for shockpads located in the UK) hardness is shown to reduce by around 5 points, which is not considered significant. The relationship between hardness and Young's Modulus indicates no significant effect of temperature on stiffness. However, as rubber is a non-linear material; this relationship cannot be directly inferred. A change of 20 to 50% in resilience over the same temperature range is considered significant. At higher temperatures more energy is returned to the impactor, which may have some effect on the ball and player interaction characteristics of shockpads.

2.3.3.3 Tyre Recycling Process

In order for tyres to be reused in shockpads, they must first be reduced to a suitable size. The size reduction methods are well described in two publications by Adhikari, De and Maiti (2000) and Klingensmith and Baranwal, (1998) and observations were also made during a site visit to a recycled rubber particulate producer.

Two main techniques for were identified for producing rubber particulate from tyres; ambient grinding and cryogenic fracture. The ambient grinding process uses a mill containing sharpened blades to gradually reduce the size of tyres. Three stages to the ambient process were observed during the visit to the rubber particulate producer, which are depicted in Figure 2.15. Post consumer tyres were sorted into passenger and truck tyres and processed separately. The first stage reduced whole tyres into smaller sections, varying in size between approximately 20 cm and 5 cm. A second stage to the process further reduced tyre sections to even smaller sections of approximately 3-4 cm. Truck tyres were subjected to a third processing stage where rubber particulate is ground until it is output in the size ranges of 2-6 or 2-8 mm for shockpad constructions. Further grinding of the rubber is conducted for the smaller sized (0.5 – 1 mm) particulate used to in-fill 3rd generation football and rugby pitches. Passenger tyres are not used processed beyond the second stage of processing, and are therefore not used to produce particulate for shockpads, as they contain higher fibre contents than truck tyres which produces a fire hazard during the final stage of processing. During each stage of the process, metal is removed by magnets and fibre removed by air separation to improve the 'cleanliness' of the final rubber produced.

Cryogenic grinding begins with tyre chips output from the first stage of the ambient grinding process. The chips are cooled in liquid nitrogen to cause the rubber to become rigid and brittle. While in this state, the tyre chips are passed through a similar mill to that used for ambient grinding to fracture the rubber and reduce its size. Particle size is controlled by immersion time in the liquid nitrogen (Adhikari et al, 2000) and the mill.

The two processes produce rubber with different physical properties. Ambient ground rubber has an irregular particle shape, from the shearing action produced by the blades, and therefore a greater surface area than the smoother and more regularly shaped cryogenically ground rubber. A benefit of the cryogenic process is that little or no heat is generated during the process. The ambient grinding procedure produces significant amounts of heat, in the order of 70 – 100 °C, which is claimed to lead to degradation of the rubber (Adhikari et al, 2000; Klingensmith and Baranwal, 1998), however no data is shown to support the extent of this degradation. The cryogenic process is also claimed to produce a 'cleaner' product free from metal, fibres and dust (Klingensmith and Baranwal, 1998).

2.3.3.4 Standard Test Methods

Some measures are taken to control the quality of the rubber particulate produced from post-consumer tyres. The American Society for the Testing of Materials (ASTM) have produced two standards that outline test procedures for measuring the quality of scrap rubber and are designated ASTM D5603-96 and ASTM D5644-96. A European Standard to characterise rubber particulate is currently being developed under the guidance of the European Tyre Recycling Association (ETRA), and is titled Post Consumer Tyres – Materials and Applications (BS EN 14243). The standard provides a classification system for products derived from post-consumer tyres and identifies test methods for to characterise the products produced.

Currently, the only standard in the UK to ensure consistency among batches of recycled rubber particulate produced for shockpad construction involves a measurement of particle size distribution and checks to ensure metal and fibre contents are low. The procedure for particle size distribution measurement is outlined in BS EN 14243, and it involves allowing the sample of rubber particulate to pass through a series of vibrating sieves. The percentage of rubber (by mass) passing through each sieve is measured resulting in a distribution similar to that shown in Figure 2.19. The standard recommends that for each size distribution, no more than 10% of the rubber particulate by mass should be larger than the maximum particle size and no more than 15% of the mass should be smaller than the minimum particle size. The standard does not specify the relative proportion of each rubber size between the minimum and maximum particle size that should be contained in a well-graded batch of particulate, allowing any proportion of different rubber sizes to be present in the mix provided they are between the maximum and minimum sizes. Magnets are used in random tests to check the particulate is free from steel and a visual inspection of fibre content is also performed. Steel content is checked for safety reasons and fibre contents are required to be minimal as they absorb binder reducing the quality available for the rubber to bond with surrounding particles.

A range of additional tests to characterise the composition and physical properties of recycled rubber particulate are also specified in BS EN 14243. The majority of compositional tests can be determined by a combination of TGA and FTIR measurements described in Section 2.3.3.1. Of the 28 physical property tests identified in the standard, only the measurements of dimensions, density, surface area and hardness are applicable to rubber particulate used in shockpad construction. The standard does not specify if these tests are required for routine testing of the particulate or if it is only required to be once. However, many of these tests specified for compositional and physical property analysis use specialised equipment that may not be practical to use for routine testing. The standard also does not set performance limits for the particulate to comply with.

This criteria for rubber particle size distribution set out by BS EN 14243 is not specified in the general standard for synthetic pitch performance requirements BS 7044, or by any sporting governing body publication and relies on agreement of a suitable rubber particle size and distribution between the particulate producer and the pitch manufacturer.

2.3.4 Polyurethane Binder

A binder is used to prevent permanent movement of rubber particulate in shockpads to retain a flat playing surface for the service life of the shockpad. Polyurethane binders are predominantly used for cast in-situ shockpad constructions in the UK, and unlike recycled rubber particulate, polyurethanes are developed with their function in mind, produced under controlled conditions and regularly tested for quality control purposes. The following section reviews the composition, physical and mechanical properties and standard tests performed on polyurethanes binders. Due to a lack of published information, the review also contains information gained through site visits to polyurethane manufacturers.

2.3.4.1 Composition

Polyurethanes (PU) are defined by the presence of urethane linkages in polymer chain backbones (Figure 2.16). PU is formed by step-growth polymerisation of a polyol, typically a polyester, polyether or hydrocarbon, with an isocyanate (Kinloch, 1987). There are numerous variations to this process, achieved by the choice of reactants and their relative amounts (Wake, 1982; Hepburn, 1982), therefore a range of products in the form of fibres, solid elastomers, coatings, sealants and adhesives can be produced.

Kolitzus (1984) claims that polyurethane was initially inferior to other products used to bind the rubber in shockpads, but was improved through a series of systematic modifications to produce a more reliable product. Advances in raw products, altering the relative proportion of reactants and exploration of the range of achievable physical properties have all contributed to this development; however, how this reliability was measured is not stated.

Various processes can be taken to form polyurethane binders (Edwards, 1986). A binder for rubber particulate is typically in the form of a one component MDI (diphenylmethane 4,4' diisocyanate) moisture cure prepolymer (Peel, 2002; Huntsman, 2000). The use of a one component prepolymer is reported to eliminate many of the problems that can occur with on-site formulation. Firstly, the prepolymer is manufactured in a laboratory, by reacting MDI (diisocyanate) with a polyol, resulting in an isocyanate-terminated intermediate product. As there is little free toxic isocyanate available after this reaction, the product has a lower volatility, more controllable reactivity (Jones, 2003) and therefore reduced risks to users. Edwards (1986) identifies that on site mixing of components is not required for one component systems, eliminating the problems of incorrect mix ratios and inadequate mixing which would have a profound effect on the mechanical properties of the final product. He does identify which mechanical properties incorrect mixing of components would affect or provide data to quantify the effect.

Conversely, Edwards (1986) claims moisture-curing PU systems are often avoided for many applications due to the production of carbon dioxide. Polyurethane is cured by the reaction of the isocyanates contained in the pre-polymer with water; forming crosslinks within the polymer over time The reaction produces carbon dioxide gas bubbles which can form voids within the binder that undermine integrity and aesthetics. However, the thin film of PU coating the rubber particles and the porous structure of shockpads allows the gas to escape making moisture curing PU suitable for shockpad constructions (Tipp and Watson, 1982). The formation of gas bubbles may limit binder content and bulk density of shockpads, however no investigations into upper limits for these shockpad design variables appear to have been conducted.

Curing of the one component PU binders relies on moisture from the atmosphere and on the surface of the rubber particles, and the levels of hydrogen available from the moisture to control the reaction rate (Hepburn, 1982; Gierenz and Karmann, 2001). The higher the temperature and relative humidity, the faster the cure, so under optimal conditions (20°C and 50% relative humidity) the binder should be dry to touch in around 8 hours and able to withstand foot traffic after 24 hours (Peel, 2002). It is a drawback of the system that it relies on environmental conditions, though they can be overcome somewhat by spraying water over the shockpad in times of low humidity (Tipp and Watson, 1982).

2.3.4.2 Physical and Mechanical Properties

The mechanical and physical properties of polyurethanes published in literature vary due to the wide range of products available in the form of fibres, solid elastomers, coatings, sealants and adhesives. This section will focus only on the properties of polyurethane binders used for the construction of shockpads.

Nagdi (1993) identifies PU as having excellent tensile strength and high resistance to degradation by oxygen and water. These properties make it suitable for use as a binder for the rubber particulate in shockpads by preventing permanent movement of the rubber particles and resisting degradation by air contained in the pores of the shockpad and during drainage of surface water.

Shockpads utilise a thin coating of PU binder over the rubber particles. The particles are compacted to produce contact points between rubber particles and bonding of the PU film occurs at these points to provide strength to the shockpad. Therefore, the thin film properties of polyurethane are of greater interest than the bulk properties of PU binders. The thin-film properties of four proprietary PU binders produced by Huntsman Polyurethanes (all suitable for shockpad construction) are shown in Table 2.10. The PU film thickness used in these tests and binder film thickness on shockpads cannot be compared as film thickness for these measurements is not stated and no investigation measuring binder film thickness of shockpads (depending on binder content) has been published.

The properties of binder viscosity, open time (time the binder is workable) and cure time affect the workability of the rubber-binder mix during compaction. High viscosities, short open times and fast cure times may also prevent flow of binder towards the bottom of the shockpad between compaction and curing, however no investigation appears to have been conducted to determine the effect of these binder variables on the binder distribution within a shockpad. There are also no details of the procedure used to measure cure time or a statement providing details of this measurement being full cure or reaching a plateau in mechanical properties, as the properties of PU are known to change over longer periods of time than those stated by Huntsman (2000).

The isocyanate content is related to the number of crosslinks that can be formed during curing, however there does not appear to be a direct relationship to tensile strength, elongation or tear resistance. Tensile strength is shown to vary widely between the four binders, with a difference of 38 MPa between the highest and lowest measurements. The properties of elongation to break and tear strength vary to a lesser extent. Tensile strength, elongation to break and tear strength of the binder will all impact the properties of the final shockpad produced. No investigation into the effect of PU mechanical properties on the mechanical properties of shockpads has been published

No further physical and mechanical property data for PU binders from other manufacturers could be found for comparison with the reviewed data. A wide range in physical and mechanical properties was shown by the Huntsman binders, and it is not known how these properties compare to binders produced by other manufacturers. In addition, no measurements of the compressive or shear properties of PU binder have been published which may be more relevant than purely tensile property measurement for shockpads placed under predominantly compressive forces by players and balls.

2.3.4.3 Standard Test Methods

Moisture-curing polyurethanes are commonly used as the binder for cast in-situ shockpads as they have been proven through constructor experience. There are no requirements for shockpad binder composition or properties published by sporting governing bodies; therefore selection of the correct binder is dependent on technical information supplied by binder manufacturer and testing conducted by the shockpad constructor.

Technical data supplied by binder manufacturers typically identifies the physical properties of the binder and safety precautions; however no mechanical property data is provided. Physical properties include density, viscosity at 23°C, isocyanate content, suitable application temperature and humidity range and time taken for the binder to withstand foot traffic. Test methods are specified for all physical tests with the exception of time taken to withstand foot traffic. No details of the test method could be found in published literature. Recommendations are also made to shockpad constructors that the binder should tested with recycled rubber particulate to ascertain its suitability in meeting the relevant standards (Conica, 2001).

Details of quality control testing conducted on polyurethanes could not be found in literature. A visit to a polyurethane manufacturer revealed physical property tests, such as density, viscosity and isocyanate content, were conducted routinely on random batches of each product to ensure correct composition and properties.

However, the specifications for the regularity of the tests and levels of acceptable deviation and how these may vary among manufacturers is not known.

2.3.5 Rubber-Binder Interface

The strength of the bond between the rubber and binder is a crucial factor in shockpad durability. The function of the binder is to maintain a constant shape to the shockpad and prevent permanent or excessive movement of rubber particles. A bond between the rubber and binder allows the binder to perform its function, as when the rubber-binder bonds break the shockpad becomes no longer functional.

The bond strength is defined by the degree with which the polyurethane binder adheres to the rubber particulate. The mechanism by which adhesion between rubber and binder occurs is not known, though many theories developed that allow quantitative accounts of events at the rubber-binder interface. It is thought that this phenomenon is actually a complex situation where many of the interactions predicted by these theories occur simultaneously (Gierenz and Karmann, 2001).

Polar (polyurethane) and non-polar (rubber) interfaces are claimed to never form strong bonds due to poor wetting (Hepburn, 1982). Polyurethane is an exception to this rule as it is also hydrophilic and will therefore absorb or displace the thin layer of atmospheric moisture found on most surfaces, allowing excellent surface contact (Hepburn, 1982). Tipp and Watson (1982) also concluded that bond strength was high from attempts to remove the thin polyurethane layer from the rubber in shockpads. Their attempt at removing the binder was conducted on cured shockpads by hand, they did not state why they were attempting to separate the rubber and binder.

Polyurethanes are claimed to bond to most surfaces (Gierenz and Karmann, 2001) and the presence of isocyanates are thought to be largely responsible. Isocyanates promote adhesion because they readily react with a variety of functional groups, are accepted by many organic substances (i.e. rubber), are polar in nature and are capable of hydrogen bonding (Hepburn, 1982). Mechanical interlocking may also account for the adhesion of polyurethane to rubber. The irregular surface of ambiently ground rubber particuate (Burford and Pittolo, 1982) may provide a source of mechanical anchorage for the binder. There appears to be little information available to support this theory in literature.

Contrary to many sources that support the bonding of rubber and polyurethane, Gierenz and Karmann (2001) state that polyurethane adhesives are only suitable for bonding non-polar elastomers after chemical activation. Chemical activation techniques such as halogenation and corona discharge increase the surface energy surface energy and polarity of the rubber (Wake, 1982). These techniques increase the chance of wetting thus increasing bond strength. While performing these techniques may increase the strength of shockpads, Gierenz and Karmann's (2001) statement is in contradiction to the fact polyurethane has been successfully used to bind rubber particulate for decades.

The tensile test (detailed in Section 2.3.2) applies a tensile force to shockpad samples to produce failure and provides a measurement of bond strength between the rubber particulate and binder. There are many factors which could influence tensile strength such as rubber type, rubber shape, rubber surface area, binder type, binder content, shockpad thickness, shockpad bulk density (number of rubber to rubber contacts), however there do not appear to be any published investigations comprehensively determining the effect of these variables on bond strength. However, the tensile test is limited in its ability to determine the bond strength (and durability) for shockpads as the test applies a tensile force where the forces applied to shockpads by players and balls were shown to be predominantly compressive forces.

2.3.6 Mix Design

Cast in-situ shockpads were shown to be composed of a mix of recycled rubber particulate and polyurethane binder compacted into a porous layer to any desired thickness. The characteristics of the constituent materials and the construction method introduce variables that may influence the mechanical properties of the shockpad they produce. These variables are termed 'mix design variables' and include:

- Recycled Rubber Particulate
    - Composition (Type)
    - Shape
    - Particle Size Range and Distribution
    - Rubber Cleanliness (Dust and fibres)
- Polyurethane Binder
    - Type
    - Binder Content
- Construction
    - Shockpad Thickness
    - Bulk Density
    - Mixing Time
    - Temperature and Humidity during Binder Cure

The effect of these mix design variables on the mechanical properties of shockpads has not been comprehensively researched. Ten mix design variables were identified as having the potential to influence the mechanical properties of shockpads, however only three have been investigated by researchers to varying degrees. Research into the effect of rubber particle size and distribution, binder content and shockpad thickness is critically reviewed in the following sections.

2.3.6.1 Rubber Particle Size and Distribution

Rubber sizes of 2 to 6 mm or 2 to 8 mm are recommended for use in sports shockpads (Charles Lawrence PLC, 2003; Stocker, 2003). No published research could be found that investigated the effect of rubber size and distribution on mechanical properties over this size range. However, Kim (1997) and Sobral (2003) studied the effect of rubber size on polyurethane-bound rubber particulate ranging in size from (0.01 to 3.9 mm).

Kim (1997) used three different rubber size ranges to investigate the effect of rubber size and distribution on tensile strength and elongation to break; fine (0.01 to 0.1 mm), average (0.7 to 2.5 mm) and coarse (2.8 to 3.9 mm). The average sized particles were mixed with the fine and course sized particles in varying weight fractions and the results are shown in Figure 2.17. Course particles sizes were shown to produce shockpads with higher tensile strength and elongation to break than the smaller particle sizes. Kim (1997) attributes lower tensile strength and elongation to break to poor binder coverage of the higher area surface smaller rubber particles. A constant binder content of 9% was used, however values for other mix design values and any appropriate controls used to limit their effect on the results is not stated.

Conversely, Sobral et al (2003) reported smaller particles sizes (0.5 to 1.5 mm) produced shockpads with higher tensile strength and reduced elongation than larger rubber sizes (2.0 to 3.0 mm). The improved tensile strength was reported to be a result of the higher shockpad density achieved though rubber size reduction. This study did not examine the effect of rubber size independently of other mix design variables, and the increased strength may be a result of increased density rather than the effect of rubber size.

The studies by Kim (1997) and Sobral (2003) do not measure effect of rubber size on the tensile properties of cast in-situ shockpads due the significant difference in rubber sizes investigated and those used in actual shockpad constructions. However, reducing rubber size and its subsequent effect on sufficient binder coverage for the increased rubber surface area is a factor requiring consideration in shockpad mix design. No measurements for the effect of rubber size and distribution on safety and player and ball interaction characteristics have been published.

2.3.6.2 Binder Content

Sporting governing bodies do not state minimum binder content required for shockpads, only stating that sufficient binder content be used to achieve a minimum tensile strength (e.g. 0.15 MPa – FIFA, 2005). Sport England (2003) recommends binder content should be at least 5% (of the rubber mass) and site visits to synthetic pitch constructions showed levels in the UK were around 9-10%.

Two studies have been conducted into the effect of binder content on shockpad mechanical properties by Kim (1997) and Tipp and Watson (1982). Kim (1997) investigated the tensile strength and elongation to break of shockpads containing 0.7

to 2.5 mm rubber particulate with binder contents of 5 to 100%. Tensile strength and elongation to break were shown to peak at 13% binder content and dramatic reductions in both properties occurred either side of this peak. The rubber size of 0.7 to 2.5 mm is significantly smaller than the 2 to 6 mm size typically used in the UK for cast in-situ shockpads and values for other mix design variables, such as bulk density, were not stated, therefore the optimal binder content of 13% may not be applicable for cast in-situ shockpads. However, the results indicate small variations in binder content may have significant effect on shockpad mechanical properties.

Tipp and Watson (1982) appears to contradict the results of Kim (1997) by showing increasing tensile strength and elongation to break with binder contents higher than 13% (Table 2.11). However, as mix design variables such as rubber size and bulk density of the shockpads are not stated, a comparison of results for the two investigations is difficult. The binder contents investigated by Tipp and Watson (1982) are also significantly higher than those typically used in the UK for cast in-situ shockpads (9-10%) and therefore do not show the effect of binder content over the required range.

The investigations into the effect of binder content on shockpad mechanical properties by Kim (1997) and Tipp and Watson (1982) does not provide results relevant to cast in-situ shockpads because of incorrect rubber size or range of binder content. Their studies also do not investigate the effect of binder content on ball and player interactions or safety.

2.3.6.3 Shockpad Thickness

An investigation by Young (2006) into synthetic hockey pitches found shockpad thickness had an effect on playing performance characteristics for both whole pitch constructions and for the shockpad layer alone. The shockpads were constructed and cured in small-scale wooden moulds, which allowed thickness to be accurately controlled, however little attention was paid to controlling other mix design variables. A Berlin Artificial Athlete and 2.25 kg Clegg Hammer were used to simulate player foot strikes on shockpads and measure shockpad mechanical properties.

Force reduction, measured by the Berlin Artificial Athlete, and the peak deceleration, measured by the Clegg Hammer, are shown to be influenced by shockpad thickness in Figure 2.20. The 25% increase in force reduction and 300g reduction in peak deceleration for varying shockpads from 6 to 20 mm are considered significant changes in player interactions. Ball interaction characteristics were also found by Young (2006) to be influenced by shockpad thickness. Ball rebound height was shown to increase with increasing shockpad layer thickness with a change of 5 cm for shockpads varying from 6 to 20 mm in thickness.

The effect of shockpad thickness on durability does not appear to have been investigated. However, the investigation into the effect of player and ball interactions has shown a significant influence of shockpad thickness.

2.4 Shockpad Behaviour and Modelling

Shockpad behaviour describes the relationship between force and deflection or stress and strain for a shockpad during the application of a load. It differs from mechanical property measurement as it describes a series of data points during loading and unloading, rather than just one data point. Measurement of shockpad behaviour provides a range of material property data such as stiffness, energy return and losses and force and deflection and also displays characteristics such as non-linear behaviour and hysteresis that must be considered for accurate modelling. Models are developed to predict the mechanical properties of products before they are manufactured (Thompson, 2001) and are therefore useful in shockpad production.

This section reviews published research investigating shockpad behaviour and models used to describe this behaviour. The lack of research specifically examining the behaviour and modelling of shockpads required this review to encompass a wider range of elastomeric materials used in sports surfaces. The modelling section examines both mechanical models and numerical models individually due to the differences between the two types of model.

2.4.1 Shockpad Behaviour

Shockpad behaviour describes the relationship between force and displacement (or stress and strain) during an impact. It is differentiated from mechanical properties as it describes the relationship between a series of points during the loading and unloading phases, whereas mechanical properties only describe one point during loading or unloading, such as peak force.

Two researchers have investigated the behaviour of shockpads and similar materials, Walker (1996) and Carré et al (2004). The two investigations differ in the method used to load the shockpad materials and the mix design of the material; however they show similar non-linear behaviour with hysteresis.

Walker (1996) used a servo-hydraulic tensometer to apply a compressive force of 1.2 kN at a controlled rate. The rate of loading is not stated, however it is described as 'quasi-static', which implies the rate is much slower than dynamic impacts that occur during actual player and ball interactions. Carré et al (2004) developed a guided impact system that allowed the impactor to fall vertically on a guidance rail and produce dynamic impacts.

Walker (1996) used the quasi-static method to investigate the behaviour of a 20 mm shockpad, a sand filled carpet and a combination of the two layers with a hemispherical indenter of 50 mm diameter. The specification of thickness is the only mix design variable defined by Walker (1996). The results of this investigation are shown in Figure 2.21, where the behaviour of the two layers and their combination show different behaviours. Carré et al (2004) used the impact guidance system to determine the impact behaviour of a bound rubber particulate athletics surface. The surface consisted of a 9 mm rubber base layer and 5 mm rough granular top layer; however, the mix design of the surface in terms of rubber type or size, binder type or content or bulk density was not described. The impact of a hemispherical head of 62 mm diameter dropped from a height of 15 cm with this surface is shown in Figure 2.22 for two different impactor mass; 2.03 kg and 3.1 kg.

The results of Walker (1996) and Carré (2004) show the same characteristics of non-linear force-displacement behaviour and hysteresis, which are also exhibited by the rubber in Figure 2.10. The non-linear gradient during loading and unloading demonstrates stiffening of the shockpad with increasing load and the hysteresis demonstrates energy lost during the impact. A similar loading behaviour is exhibited for both impactors by Carré et al (2004) in Figure 2.22, however the increase in the size of the hysteresis loop for the larger mass shows shockpad behaviour is dependent on impactor mass. Peak forces reached by both investigations are similar (1.2 kN compared with 1.5 kN), however the peak deflections are halved for the dynamic impacts produced by Carre et al (2004). This difference may be explained by the strain-rate dependency of rubber behaviour, where the slower rates of loading used by Walker (1996) allow higher deflections to be reached than for those of dynamic impacts from players and balls.

Further investigation conducted by Carré et al (2004) showed shockpad behaviour to be dependent on impactor shape, surface area and mass and impact velocity, which reflects the results of mechanical property tests conducted by Nigg and Yeadon (1987) and Nigg et al (1990). For ball impacts, the Coefficient of Restitution (COR) is a measure of ball rebound height. Carré et al. (2004) found impactor shape to have great influence on COR, with a hemispherical hammer judged to most accurately represent sports ball impacts. COR data was found to be independent of impact velocity but dependent on mass, with hysteresis loops significantly increasing in size with increasing mass.

The investigations conducted by Walker (1996) and Carré et al (2004) show the compressive behaviour of shockpads to be non-linear and hysteretic and that the different mass involved in ball and player impacts produced different shockpad behaviour. Carré et al (2004) focuses on the effect of the impactor, however they did not compare the behaviour for a typical ball and player impact. Mechanical properties were shown to vary with shockpad thickness by Young (2006) (Section 2.3.6); however there has been no investigation into the effects of mix design on shockpad behaviour.

2.4.2 Mechanical Models

Mechanical models use two elements, a spring and a dashpot, to represent the behaviour of materials. The simplest mechanical model used to describe the behaviour of rubber and other elastomeric materials is called a Kelvin-Voight Model, shown in Figure 2.23. The model is represented by a spring and dashpot in a parallel configuration; the spring representing the elastic (recoverable) component of deformation and the dashpot representing the viscous (loss) component. The force components in the spring and damper are given by Equation 2.4 and 2.5 respectively. Due to their parallel configuration, individual forces for each component are additive to provide total force given by Equation 2.6. Displacement and velocity are input into the model and transmitted force is output. The magnitude of force is adjusted though altering spring stiffness and the damping coefficient.

This mechanical model has been used by researchers such as Leonard (1973) and McCullagh and Graham (1985) to describe elastomeric materials. McCullagh et al (1985) specifically used the Kelvin-Voight Model to describe elastomeric sports surfaces and found the model was capable of describing the hysteresis loop, but did not adequately describe the material behaviour due to the constant stiffness of the spring. No values for model coefficients, k or c, or a graphical comparison between model and material behaviour were provided in the publication.

$$F_s = kx \quad \text{--------} \quad \text{Equation 2.4}$$

$$F_d = c\dot{x} \quad \text{---------} \quad \text{Equation 2.5}$$

$$F_T = F_s + F_d = kx + c\dot{x} \quad \text{--------} \quad \text{Equation 2.6}$$

Where:

F_s	=	Spring Force	[N]
F_d	=	Damping Force	[N]
F_T	=	Total Force	[N]
k	=	Spring Stiffness	[N/m]
x	=	Displacement	[m]
c	=	Damping Coefficient	[N.sec/m]
$\dot{x}$	=	Velocity	[m/sec]

McCullagh et al (1985) also presented a modified Kelvin-Voight Model, whereby the linear spring was replaced by a non-linear spring to provide non-linear stiffness. The modified model equation is given by Equation 2.7, where n represents a non-linear coefficient. McCullagh et al (1985) used a non-linear coefficient of 2 and concluded that a reasonable approximation to material behaviour could be achieved. However, again no values for other model coefficients, k and c, or a graphical comparison between model and material behaviour was provided.

$$F_T = kx^n + c\dot{x} \quad \text{---------} \quad \text{Equation 2.7}$$

Hertzian Contact Theory is similar to the non-linear Kelvin-Voight Model as it uses a non-linear spring; however the effect of damping is not considered. The theory models the effect of a rigid spherical mass impacting an elastic material, concluding that the relationship between force and deflection is given by Equation 2.8, where the non-linear coefficient is equal to 1.5 (Johnson, 1985).

$$F = kx^{1.5} \quad \text{--------} \quad \text{Equation 2.8}$$

The spherical shape of the mass is intended to represent a player's heel or a ball impacting a synthetic sports pitch. Shorten and Himmelsbach (2002) used Hertzian Contact Theory to describe the behaviour of a playground surface and an in-filled synthetic carpet. Results, shown in Figure 2.24, indicated that sports surfaces do not act with perfectly elastic behaviour and that by altering the non-linear coefficient from 1.5, behaviour could be more accurately described. The non-linearity coefficient, n, was claimed to be dependent on surface properties and contact geometry between the spherical mass and surface.

The modified Hertzian model developed by Shorten and Himmelsbach (2002) described linear materials (n=1), Hertzian contact (n=1.5), materials that stiffen (n>1) and materials that soften (n<1) with deformation. The model is limited to describing only the loading phase of impacts as it is not able to describe energy loss that occurs during unloading. A combination of the non-linear damped model developed by McCullagh et al (1985) and the variable non-linear model developed by Shorten and Himmelsbach (2002) may provide the most accurate model for describing the behaviour of sports surfaces, however no investigation of this combined model could be found in literature. Further to this, no composite mechanical model that described the overall behaviour of a synthetic surface as individual models of carpet, shockpad and foundation layers could be found in this review.

2.4.3 Numerical Models

Numerical models typically employ Finite Element Analysis (FEA) which involves the material being divided into a mesh of small elements with shared points between mesh called nodes, shown in Figure 2.25. A complex equation to describe the relative movement of the nodes according to material coefficients is input into a computer software programme which is capable of approximating a solution. Numerical models offer more scope for modelling complex structural details and sophisticated materials than mechanical models but as it is an approximate method it contains sources of error (Thomson, 2001).

Thompson (2001) and Kim (1997) have used numerical models to describe sports surface materials. Thompson (2001) used a computer programme called ABAQUS to approximate the behaviour of a non-linear, rubber treadmill surface. Model coefficient, μ_i, represents material stiffness and their summation is equal to the initial material modulus of 2 MPa. The power stiffening index, α_i, controls the rate of stiffening; for this surface a value of -25 was found to provide the best fit. The model output, strain energy, allowed stresses to be derived through differentiation with respect to stretch ratio, a measure of strain. The force deflection behaviour of the surface is compared to the model prediction in Figure 2.26. At small strains, less than 1 mm, the model compares well to experimental data; however, at larger strains the model does not show the same degree of non-linearity.

Kim (1997) also used a numerical model to describe the behaviour of polyurethane bound rubber particulate shockpads. The numerical model differs from that used by Thomson (2001) as it directly outputs stress for a given strain. A comparison of model and experimental data is shown in Figure 2.27, which appears to compare well however, even for very large strains of 200%, the data and model show linear behaviour where it was noted by other researchers that shockpads exhibit marked non-linear behaviour (e.g. Walker, 1996).

The numerical models used by Thompson (2001) and Kim (1997) do not describe hysteresis as this is claimed by Thompson (2001) to account for a small fraction of the total energy cost of running. This may be true for models of treadmill surfaces which are only concerned with running; however, energy losses in sports pitches play an important role in the ball interactions and therefore hysteresis must be considered for a model to be suitable. In addition, the inability of the model presented by Kim (1997) to describe non-linear behaviour makes it even less suitable for describing shockpad behaviour.

In principle, mechanical and numerical models are similar in terms of material property data, input and outputs. Both types of model use inputs of deflection or strain and material constants that control stiffness and rate of stiffening to obtain an output of force or stress. Numerical models examine the behaviour of a material as a number of smaller elements and therefore can supply more information regarding strain gradients across the thickness of the material than mechanical models which treat the surface as a single element. However, numerical models are complex and insufficient material property data and an inexact model and boundary conditions can lead to inadequate solutions. Current numerical models are also not able to describe hysteresis, which would be an essential requirement to modelling ball interactions.

2.5 Discussion

The literature review has provided a critical review of published literature describing outdoors synthetic sports pitches for hockey, football and rugby with its focus on the shockpad layer of the pitch. This section provides a discussion of the current state of knowledge regarding shockpad layers and outlines the main areas requiring further investigation that were highlighted throughout this review.

The majority of research into synthetic sports pitches regards the pitch as a single element. However, synthetic sports pitches are composite structures, composed of foundation, shockpad and carpet layers. Each layer is constructed from distinctly different materials and therefore exhibits different mechanical properties and behaviour. The role of the foundation layer is to provide a solid and level base to the surfacing layers. The surfacing layers consist of shockpad and carpet layers and were identified as being crucial in determining player and ball interaction characteristics.

The carpet layer has undergone research and development by manufacturers from the 'astro turf' introduced in the 1960's, to sand-dressed and sand-filled carpets, to the 3rd generation and water based carpets currently in use. However, shockpad layers have not undergone the same level of development, with observed current industry practice being the same as that described by Tipp and Watson in their 1982 publication. The slow rate of development to optimise shockpad design for performance is attributed to a lack of comprehensive scientific investigation of this layer, with the current state of knowledge regarding shockpad mix design and site practice during construction a result of constructor experience and basic (unpublished) testing conducted by synthetic pitch constructors. This lack of comprehensive knowledge of the shockpad is layer is reflected in the barely-existent standards for design specifications and performance published by sporting governing bodies.

The review of literature showed a lack of scientific research into fundamental aspects of shockpad mix design, mechanical properties, suitable test methods and behaviour and also a model to accurately describe this behaviour. This lack of comprehensive investigation was most evident for shockpads mix design, where only three of the ten variables identified as having the potential to influence mechanical properties and behaviour of the shockpad were examined, and to a limited extent. In addition, Young (2006) was the only researcher to specifically investigate the effect of cast in-situ shockpad mix design using a suitable 2- 6 mm rubber size.

The investigation of shockpad thickness conducted by Young (2006) and the secondary research of binder content and rubber size and distribution using smaller rubber sizes by Kim (1997), Sobral (2003) and Tipp and Watson (1982) demonstrated a strong effect influence of mix design variables on mechanical properties of shockpads. However, their research does not provide comprehensive knowledge of the effect of all mix design variables on mechanical properties such as player and ball interaction characteristics, durability and safety. There is also insufficient identification of key variables that may require tight control during shockpad construction to reduce variation of these mechanical properties across the pitch and between different synthetic pitch constructions.

Six of the ten identified mix design variables result from the constituent materials used to construct shockpads, however there is no limits placed on the types of materials or their properties by sporting governing bodies. The recycled rubber particulate which is typically used for shockpad constructions can vary according to composition, shape, particle size and size distribution and also cleanliness. Neither the composition of recycled rubber particulate nor the various different rubber compounds used to construct post consumer truck tyres could be well established from literature. The particle shape, particle size distribution and cleanliness vary according to the granulation method used. Currently, only particle size and distribution of rubber particulate are measured by particulate suppliers to ensure consistency between different batches of product; however there is no provision of a well-graded rubber distribution for comparison or to ensure consistency among suppliers. The mix of different rubber compounds suggests recycled rubber particulate may be a variable product in terms of its composition and physical and mechanical properties and also has the additional variables of shape, cleanliness and size and distribution. The recycled rubber has not been well characterised in literature and its potential to influence the mechanical properties and behaviour of shockpads has not adequately assessed.

Conversely, the polyurethane binder is specifically manufactured for the purpose of binding rubber particulate and is produced under factory conditions. The composition of the binder and its effect of changes on mechanical properties are well understood by manufacturers who also conduct comprehensive routine testing for quality control purposes. For these reasons, the polyurethane binder does not require to the same level of characterisation as the recycled rubber particulate. However, the effect of temperature and humidity and how the mechanical properties of a shockpad change with cure time are not well known and require further research.

Observations made during site visits to shockpad construction sites highlighted potential areas where variation from mix design specifications may occur. The inaccurate method for measuring binder quantity and insufficient mixing time for the rubber and binder may potentially lead to variations in binder content locally and across the shockpad. Further potential sources of mix design variation were observed in the operation of the oscillating levelling beam which controls both thickness and compaction density during shockpad construction.

Current test methods specified by sporting governing bodies to ensure mix design specifications are met are not capable of identifying poor site practice in shockpad construction. Shockpad design for hockey, rugby and football pitches typically vary only in the specified thickness of the layer, however, testing specifications for mix design verification published by the relevant governing bodies differ. FIH, the governing body for hockey, do not require any verification of mix design specifications. Mass per unit area is a measure of compacted density and is required by UEFA, FIFA, FA and the IRB. The value of mass per unit area will depend on shockpad thickness as more rubber and binder is required to make a thicker shockpad over the same area and is therefore not directly comparable between shockpads of different thickness. Thickness measurements are also required by UEFA and the FA and tensile strength required by UEFA and FIFA as a measure of sufficient binder content. UEFA are the only governing body to specify all three tests to determine compaction density, shockpad thickness and binder content. However, with the exception of tensile strength, test results are irrelevant as there are no limits placed on acceptable tolerances for each mix design variable to identify poor construction quality. In addition, these tests may be conducted on samples constructed alongside the shockpad construction which may not be representative of the in-situ construction.

Tensile strength is used to indicate sufficient binder content and durability in shockpads and is required by FIFA to be at least 0.015 MPa. This minimum strength criterion is adopted from the IAAF standards for athletics tracks, which typically use much higher binder contents, smaller rubber sizes and higher compacted densities than shockpads and therefore may be higher than necessary. There appears to be no specific investigation into the relationship between binder content and durability specifically for cast in-situ shockpads to justify the stipulation of a 0.015 MPa minimum strength requirement or quantify the extent that other mix design variables may affect tensile strength. In addition, the tensile test measures only one aspect of shockpad failure, where rubber-binder bonds degrade and rubber particulate becomes mobile, and does not account for other methods of failure such as excessive mechanical property changes that affect player safety and ball and player interactions. The tensile test places a sample of the shockpad in pure tension and is a rapid test used to produce failure in the shockpad. It does not simulate the predominantly compressive and shear forces applied by athletes and balls or environmental factors which produce degradation of the rubber-binder bonds and changes in mechanical properties over time.

Shockpad durability is one aspect of performance that is required to be measured by FIFA, however, further performance tests measuring the response of player and ball interactions are typically only required to be conducted on completed synthetic pitches. There are no requirements for ball interaction characteristics for the shockpad layer and UEFA are the only sporting governing body to require indirect player interactions to be measured. UEFA state that a force reduction value of 20-70% is acceptable for the shockpad layer. This range is very wide, only eliminating very compliant and the very stiff shockpads, and is far wider than the requirements set by governing bodies once the carpet layer has been installed. This lack of performance testing of the cured shockpad layer prevents identification of areas where ball and athlete interaction characteristics may vary from the remainder of the pitch which will not be identified until after carpet installation.

The Berlin Artificial Athlete is criticised in literature not accurately simulating a player impact with the sports surface as it only considers vertical interactions with no consideration for the effect of different player mass or various movements and also for being too heavy and cumbersome. Young (2006) trialled the use of a 2.25 kg Clegg Hammer as an alternative test to the Berlin Artificial Athlete on shockpads layers and whole synthetic pitches. The Clegg Hammer provided a similar energy input to the Berlin Artificial Athlete, but provided a shorter contact time with the surface. While the test did not overcome some of the issues with the AAB, such as purely vertical impacts, the test did show potential for the use as a rapid and portable test to measure changes of shockpads thickness in-situ, however its ability to detect changes in other mix design variables was not investigated. Overall, there is a lack a suitable test methods to verify shockpad mix design and performance to ensure good site practice is followed. Further investigation of potential test methods, such as the Clegg Hammer test, and suitable alternatives to the tensile test (to provide accurate binder content and durability measurements) should satisfy this requirement and prevent excessive changes in mechanical properties across the pitch and between different pitch constructions.

Mechanical properties descibe specific aspects of shockpad behaviour, such as peak impact force or stiffness. As shockpad mechanical properties were shown to be influenced by mix design, an effect on shockpad behaviour is also anticipated. Shockpad behaviour was investigated by Walker (1996) and Carré et al (2004) and shown to be non-linear with hysteresis. However, there has been no investigation into the effects of mix design on shockpad behaviour. Carré et al (2004) focused on the impactor and showed shockpad behaviour to be influenced by impactor shape, surface area, mass and impact velocity, however specific mass, shapes and impact velocities relevant to actual player and ball interactions were not examined and the design of shockpads used were not well detailed. Information regarding the effect of mix design and behavioural data for actual or accurately simulated ball and player interactions are both required to develop an accurate model to describe shockpad behaviour.

A model for behaviour is required to accurately describe characteristics of shockpad behaviour such as non-linearity and hysteresis. The review of numerical models revealed they were capable of providing detailed information, such as the magnitude of strain gradients across the thickness. However, the inability of the reviewed numerical models to describe hysteresis, which is fundamental for modelling ball interactions, makes them less suitable for modelling shockpad behaviour. In addition, the literature review found no suitable mechanical models that were able to describe both variable non-linear behaviour and hysteresis. A combination of the non-linear damped mechanical model presented by McCullagh (1985) with the variable non-linearity coefficient of the spring element described by Shorten and Himmelsbach (2002) offers potential for the development of a model to describe shockpads.

Further research in the areas of mix design, mechanical properties, suitable test methods, shockpad behaviour and modelling will assist the synthetic sports pitch construction industry and academia, and consequently synthetic pitch users. The synthetic pitch construction industry will benefit from a clearer understanding of shockpad layers particularly with the identification of key mix design variables which are useful for both improving site practices to reduce variability in mechanical properties and for optimising shockpad performance. The additional benefit of further test methods for mix design verification and performance measurement will also assist in identifying areas requiring relaying prior to carpet installation. Knowledge of shockpad mechanical properties and behaviour will assist in academic research into whole pitch constructions and also the development of composite models which examine the interactions between players, footwear and the surface and injuries, performance and safety.

2.6 Summary

The literature review revealed a lack of detailed scientific investigation into shockpad layers and highlighted many areas in need of further research. Key areas in need of further research include mix design, mechanical properties, suitable test methods, shockpad behaviour and modelling.

Shockpad mix design was shown to be a crucial area in need of further research. Mix design incorporates variables from constituent materials, construction and curing that have the potential to the influence mechanical properties and behaviour. The potential for mechanical property variation due to the recycled rubber particulate could not be ascertained from published literature and therefore requires further research. The polyurethane binder was determined to have less potential for variation due to it being manufactured in controlled factory conditions and regularly tested for quality control purposes. Observations made during shockpad construction visits revealed numerous areas for potential variations in mix design particularly with binder content, mixing, compaction and curing conditions. Shockpad thickness was shown by Young (2006) to significantly influence athlete and ball interactions; however the effect of other mix design variables on shockpads is not known.

Test methods to ensure mix design specifications and performance characteristics for shockpads are met were not consistent among various sporting governing bodies and currently do not provide an adequate assessment of the shockpad layer prior to carpet installation. The development of improved test methods and stipulation of acceptable ranges for performance is required to ensure consistent player and ball interactions characteristics are produced across the pitch and that good site practice is followed during shockpad construction and cure.

The impact behaviour of shockpads during player and ball interactions is not a well researched area. The effects of mix design on shockpad behaviour are not described in literature, with more focus placed on the effect of changing the impactor. This lack of knowledge regarding shockpad behaviour has prevented the development of a suitable model to describe player and ball impacts and also an understanding of how mix design may affect the model coefficients.

Further research in these areas will provide a clearer understanding of their mechanical properties and behaviour to benefit both the synthetic sports pitch construction industry and academic research and consequently synthetic pitch users.

	Sand Filled	Sand Dressed	Water Based	3rd Generation
Pile	Medium	Long, less dense	-	Long
In-fill	Sand	Sand	Water	Rubber, Sand
Uses	H, F, T, MUGA	H, F, T, MUGA	H	F, R

H = Hockey R = Rugby F = Football T = Tennis

Table 2.1: Common artificial turf varieties
(Adapted from text in Crawshaw, 1989)

Author	Velocity	Surface	Move	Vertical F_{max}	Horz. F_{max}	Contact Time [sec]
Adrain and Xu (1990)	Typ[a]	Force Plate	Walking	1.33 BW	0.25 BW	1.1
			Running	2.50 BW	0.33 BW	0.3
			Veering	2.00 BW	0.83 BW	0.3
			Cutting	2.00 BW	0.67 BW	0.65
			Stopping	2.67 BW	3 BW	0.5
			Dodging	2.67 BW	0.67 BW	0.9
			Pivoting	2.67 BW	0.17 BW	1
			Jumping	2.00 BW	0.33 BW	1
			Landing	3.33 BW	1 BW	0.5
			Lunging	2.67 BW	0.75 BW	1
Ozguven and Berne (1988)	-	Gym Mat	Jumping	5.70 BW[b]	-	-
Nigg and Yeadon (1987)	4 m/sec	Track 1	Running	1458 N	-	-
		Track 2		1419 N	-	-
Munro et al (1987)	3 m/sec	Force Plate	Running	1.57 BW	-	-
	4 m/sec			1.95 BW	-	-
	5 m/sec			2.32 BW	-	-
Dixon et al (2000)	3 m/sec	Asphalt	"	1.6 BW	-	-
		I.A.A	"	1.58 BW	-	-
Blackburn (2005)	-	3G Pitch	45° Cut	3250 N	2000 N	0.225

a- Movement speed typical of hockey or basket ball
b- Mean of results c- Impact Absorbing Asphalt BW = Body weight

Table 2.2: Peak Force measurements for various researchers

	Researcher	
	Petersen et al. (2004)	Spencer et al. (2004)
Movement	**Hockey - Female**	**Hockey - Male**
Standing	69.2 %	7.4 %
Walking		46.5 %
Jogging	21.2 %	40.5 %
Slow Running	4.5 %	4.1 %
Moderate Running	2.6 %	1.5%
Fast Running	1.4 %	
Sprinting	1.2 %	

Table 2.3: Comparison of sporting movement velocity using GPS player tracking

Condition	Problems
Moisture	Degradation
Oxygen, UV Light	Degradation
Pollution	Degradation & Drainage blockages
Temperature Variations	Dimensional instability & Property variations

Table 2.4: Environmental conditions and problems
(Adapted from text in Tipp and Watson, 1982)

		Hockey			Rugby	Football			
		FIH Starter	**FIH Standard**	**FIH Global**	**IRB**	**FIFA 1 Star**	**FIFA 2 Star**	**UEFA**	**FA**
Player Interaction									
Force Reduction	%	30 - 65	40 - 65	40 - 65	60 - 75	55 - 70	60 - 70	> 60	> 55
Vertical Deformation	mm	-	-	-	4 - 10	4 – 9	4 - 8	< 10	4 - 12
HIC – Critical Drop Height	m	-	-	-	> 1.0	-	-	-	-
Rotational Friction	Nm	-	-	-	30 - 50	25 -50	30 - 45	30 - 45	30 - 50
Slip Resistance		0.6 – 1.0	0.6 – 1.0	0.6 – 1.0	0.6 – 1.0	-	-	-	-
Ball Interaction		1.5 m Drop Height				2.0 m Drop Height			
Ball Rebound	m	0.1 – 0.4	0.1 – 0.3	0.1 – 0.25	30 – 50%	0.6 – 1.0	0.6 – 0.85	0.6 – 0.85	0.6 – 1.0
Ball Roll	m	5 – 20	5 - 15	9 - 15	-	4 – 10	4 – 8	4 – 8	4 - 10

Table 2.5: Summary of performance specifications for football (FIFA, 2005; FA, 2005; UEFA, 2003), hockey (FIH, 1999) and rugby (IRB, 2005)

Specification		Stuttgart	Berlin
Dropping Mass	[kg]	50	20
Spring Constant	[kN/m]	50	2000
Drop Height	[mm]	30	55
Test Foot Diameter	[mm]	50	70
Contact Velocity	[m/sec]	0.7 approx	1.0 approx
Time of Peak Force	[msec]	150 approx	10 approx

Table 2.6: Specifications for Artificial Athlete Stuttgart and Artificial Athlete Berlin (Kolitzus, 1984)

Property	Control	Site A	Site B
Thickness [mm]	16.0	11.6 – 17.5	10.5 – 16.3
Weight/Unit Area [kg/m^2]	11.2	5.1 – 8.2	4.2 -7.5
Density [g/cm^3]	0.70	0.41 – 0.47	0.37 – 0.50
Tensile Strength [kPa]	1100	90 – 370	130 – 260
Elongation at break [%]	142	60 - 112	39 - 83

Table 2.7: The effect of incorrect mixing and/or inadequate compaction on the physical properties of a polyurethane bound rubber particulate system (Tipp and Watson, 1982)

Authority	Sport	Testing Requirement	Standard	Performance
UEFA (2003)	Football	Material Identification	Visual	-
		Force Reduction	M	20 – 70 %
		Mass/Unit Area	M	1-25 kg/m^2
		Thickness	M	-
		Tensile Strength	M	-
FIFA (2005)	Football	Tensile Strength	EN 12230	0.15 MPa
		Mass/Unit Area	EN 430	-
		Compressive Modulus	ISO 604	-
FA (2005)	Football	Construction	Visual	-
		Manufacturer	M	-
		Thickness	BS EN 1969	-
		Mass/Unit Area	EN 430	-
IRB (2005)	Rugby	Compressive Modulus	ISO 604	-
		Mass/Unit Area	EN 430	-

Table 2.8: Shockpad test criteria for pitch certification

Researcher	Source	Volatiles [%]	Rubber [%]	Carbon Black [%]	Ash [%]
Rouse (1997)	Truck Tread	12	50	33	5
	Car Tyre	15	48	32	5
Cui et al (1999)	Tyres	65		32	3
Manuel and Dierkes (1997)	Various NR	14	52	30	4
	Inner liner	11	53	33	4
Klingensmith et al (1998)	Rubber	10 -14	45 - 52	30 - 31	6 - 7
Bloxham (1962)	Tyres	10 - 15	-	20 - 25	10 - 15

Table 2.9: Summary of composition for recycled rubber particulate

Property		Product 1	Product 2	Product 3	Product 4
Isocyanate content	[%]	10	9.5	10	9.3
Viscosity (25°C)	[cps]	2000	2800	2600	2700
Open Time	[hrs]	2	4	2	2.5
Cure Time (50% R.H.)	[hrs]	34	42	29	30
Tensile Strength	[MPa]	7.98	12.84	15.24	46.25
Max. Elongation	[%]	371	517	533	529
Tear Resistance	[kN/m]	70.82	88.35	74.32	89.22

Table 2.10: Physical and mechanical properties of thin-film polyurethanes.
(Data taken from Huntsman, 2000. Converted to S.I. units)

Binder [%]	Tensile Strength [MPa]	Elongation at Break [%]
17	1.01	92
20	1.31	96
23	1.53	101

Table 2.11: Effect of binder content on tensile strength and elongation to failure
(Tipp and Watson, 1982)

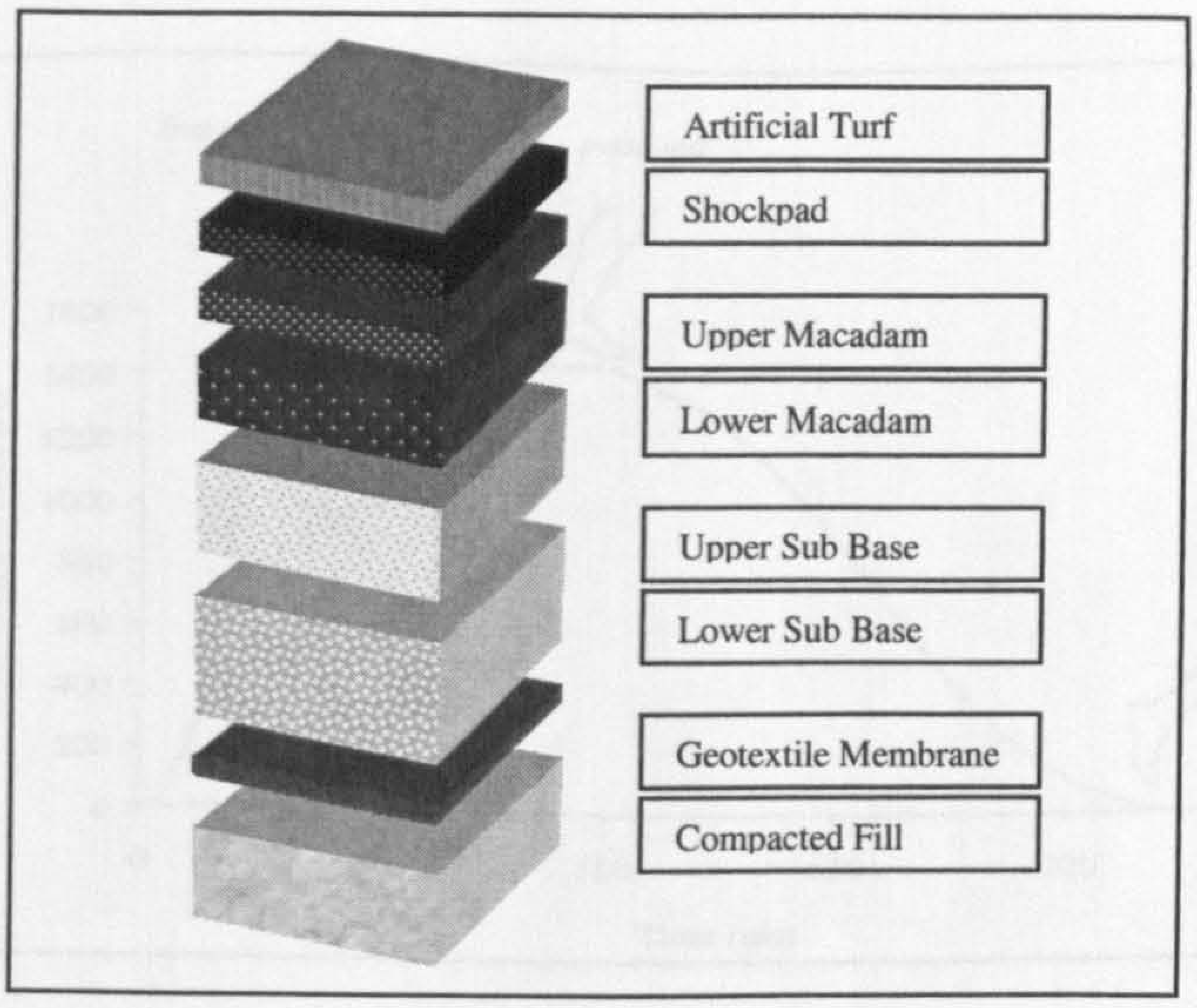


Figure 2.1: Typical structure of a synthetic sports pitch (Fleming et al, 2002)

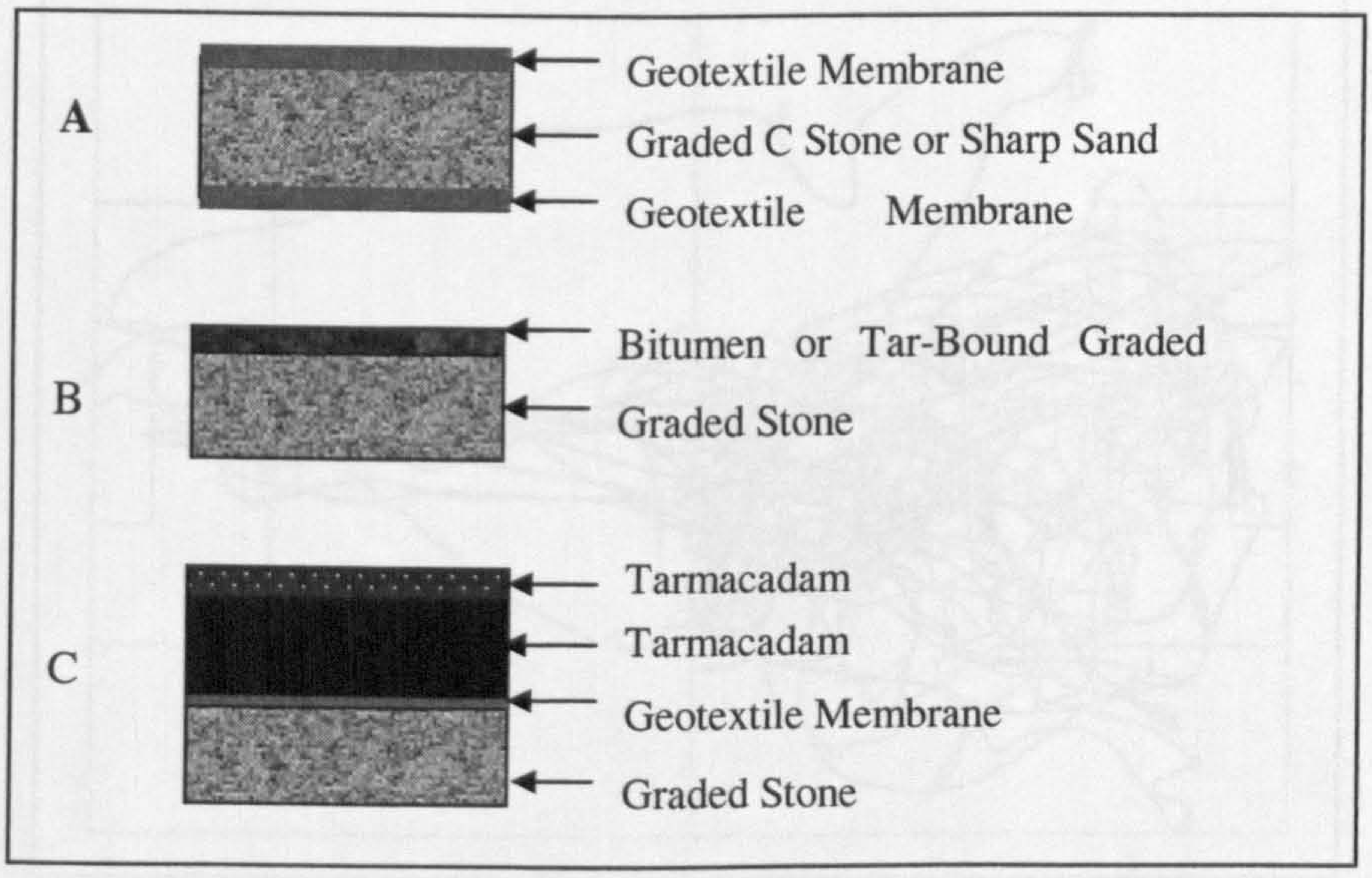


Figure 2.2: Typical structure of foundations for synthetic sports pitches (a) dynamic, (b) semi-bound and (c) bound

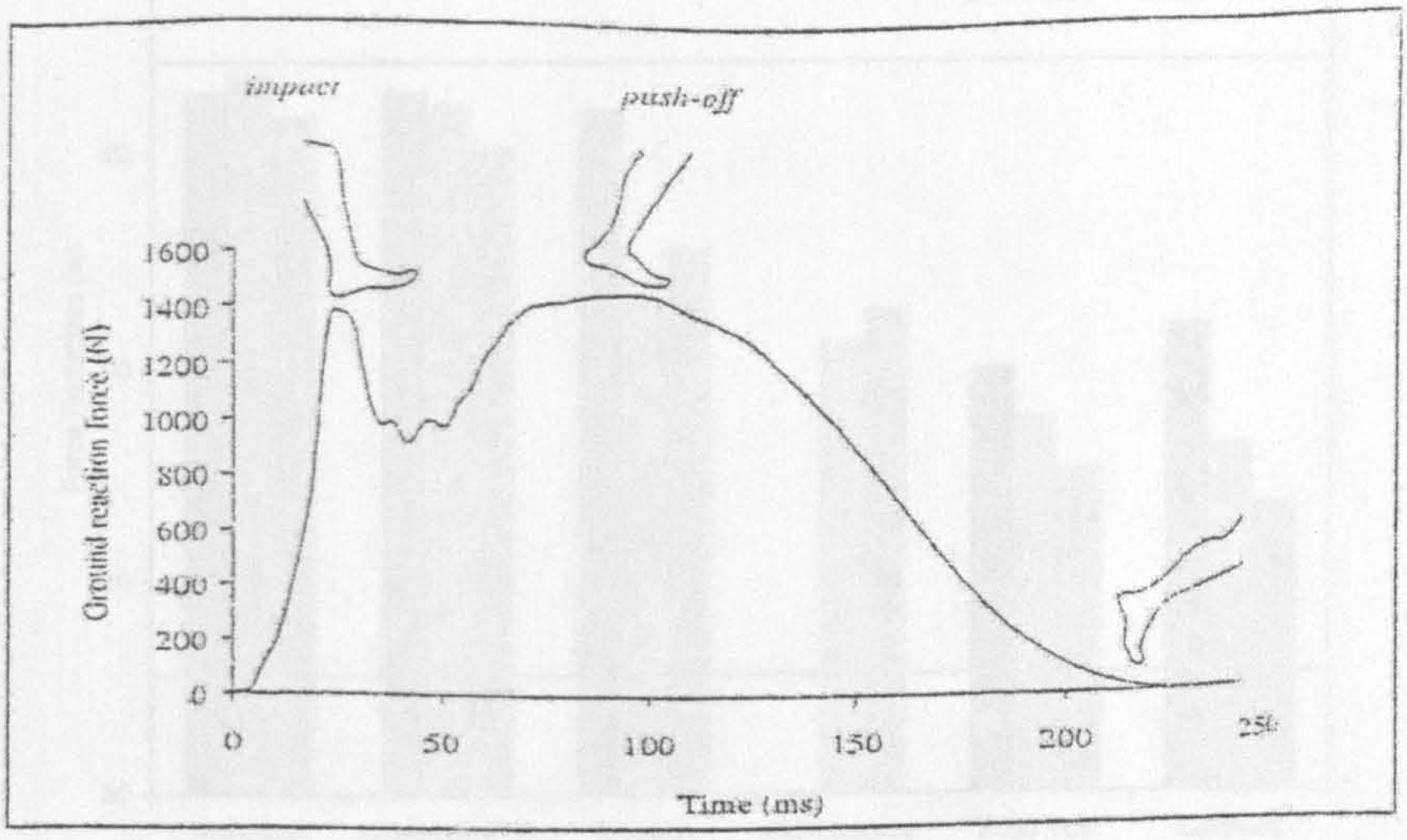


Figure 2.3: Force-time history for heel-toe impact (Dixon et al, 2000)

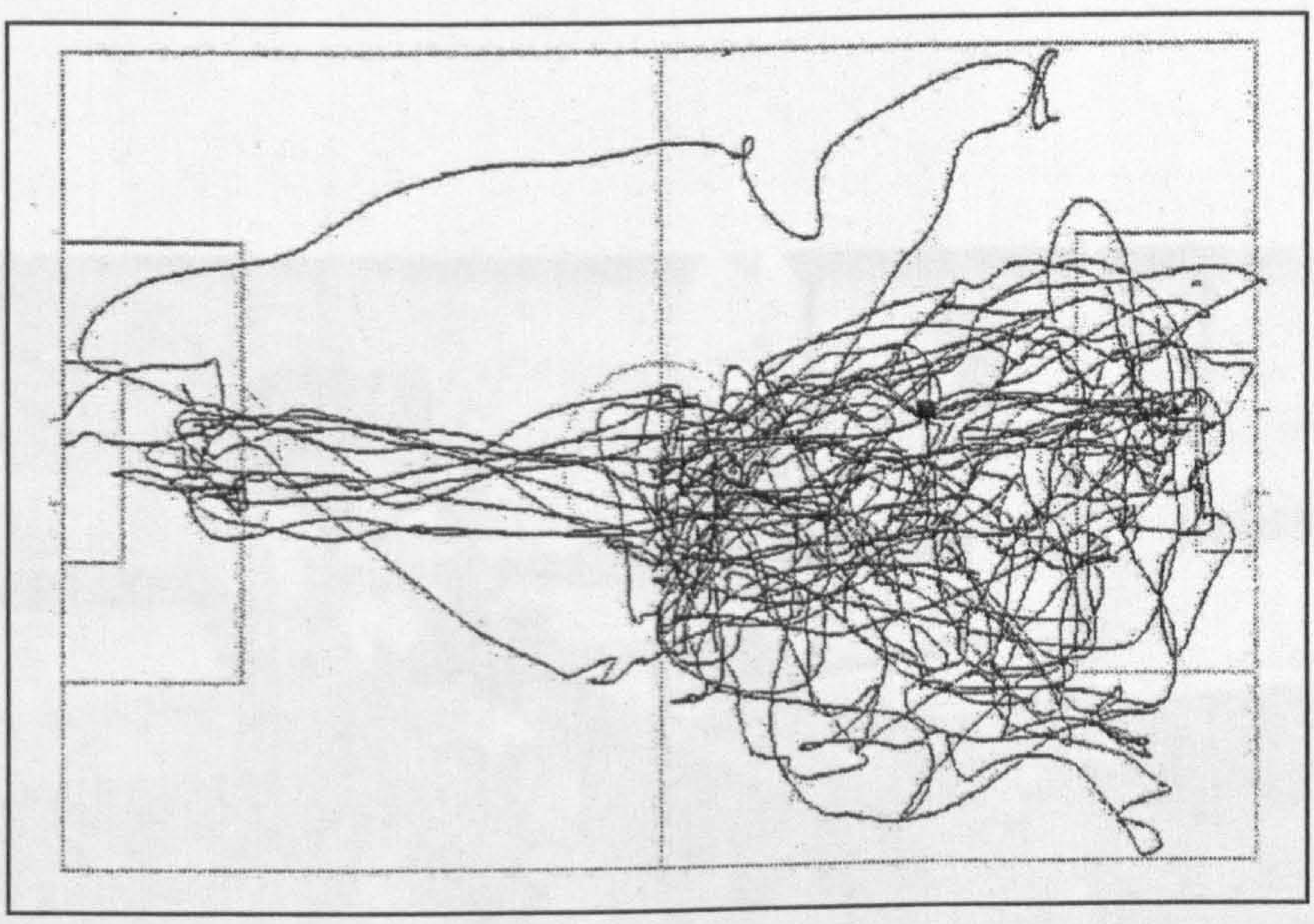


Figure 2.4: Movement of one player across a football pitch in a 45 min period tracked by GPS (Figueroa et al, 2005)

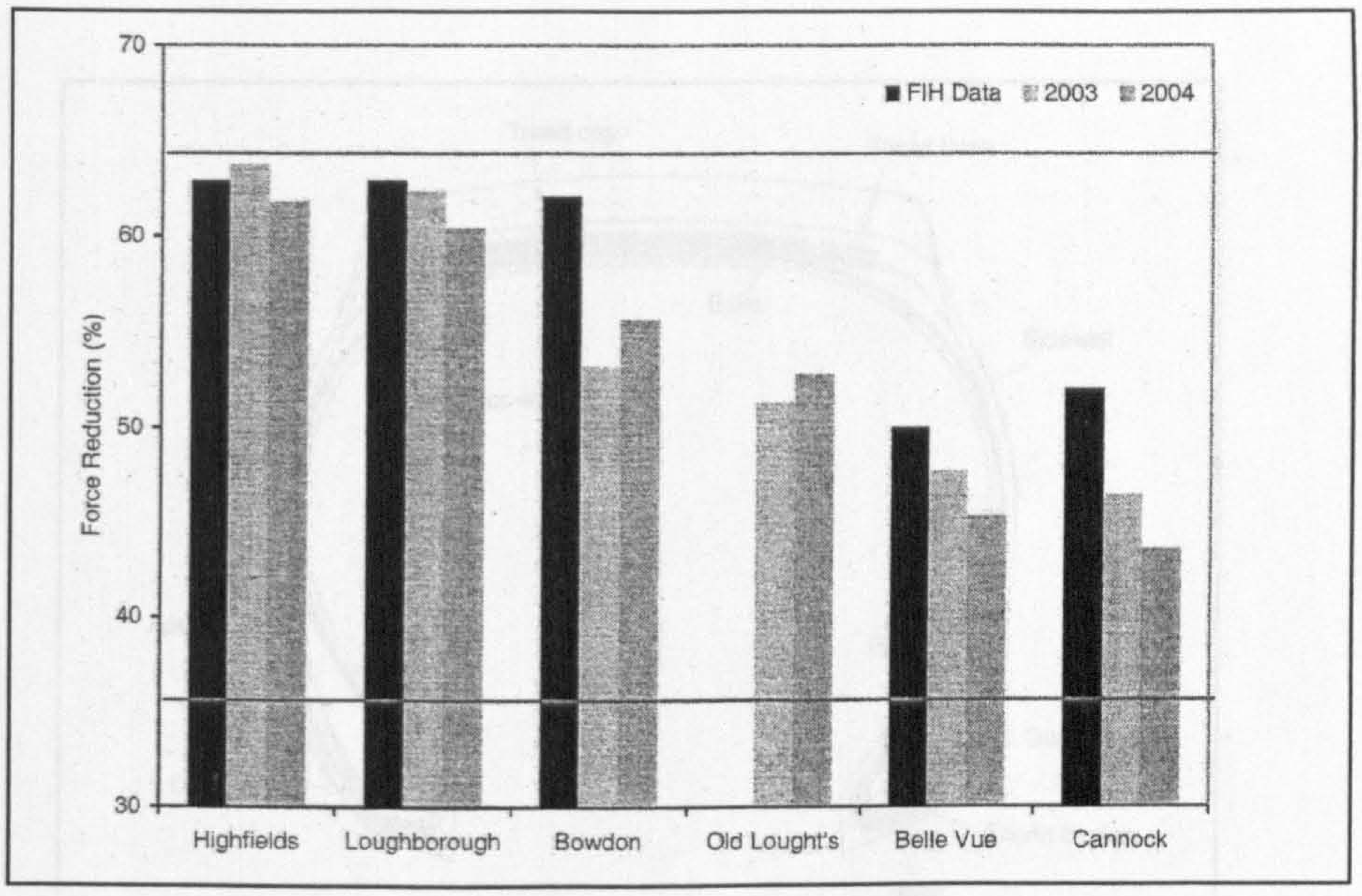


Figure 2.5: Force reduction changes measured by the Berlin Artificial Athlete due to pitch degradation over a three year period for water based hockey pitches (Young, 2006)

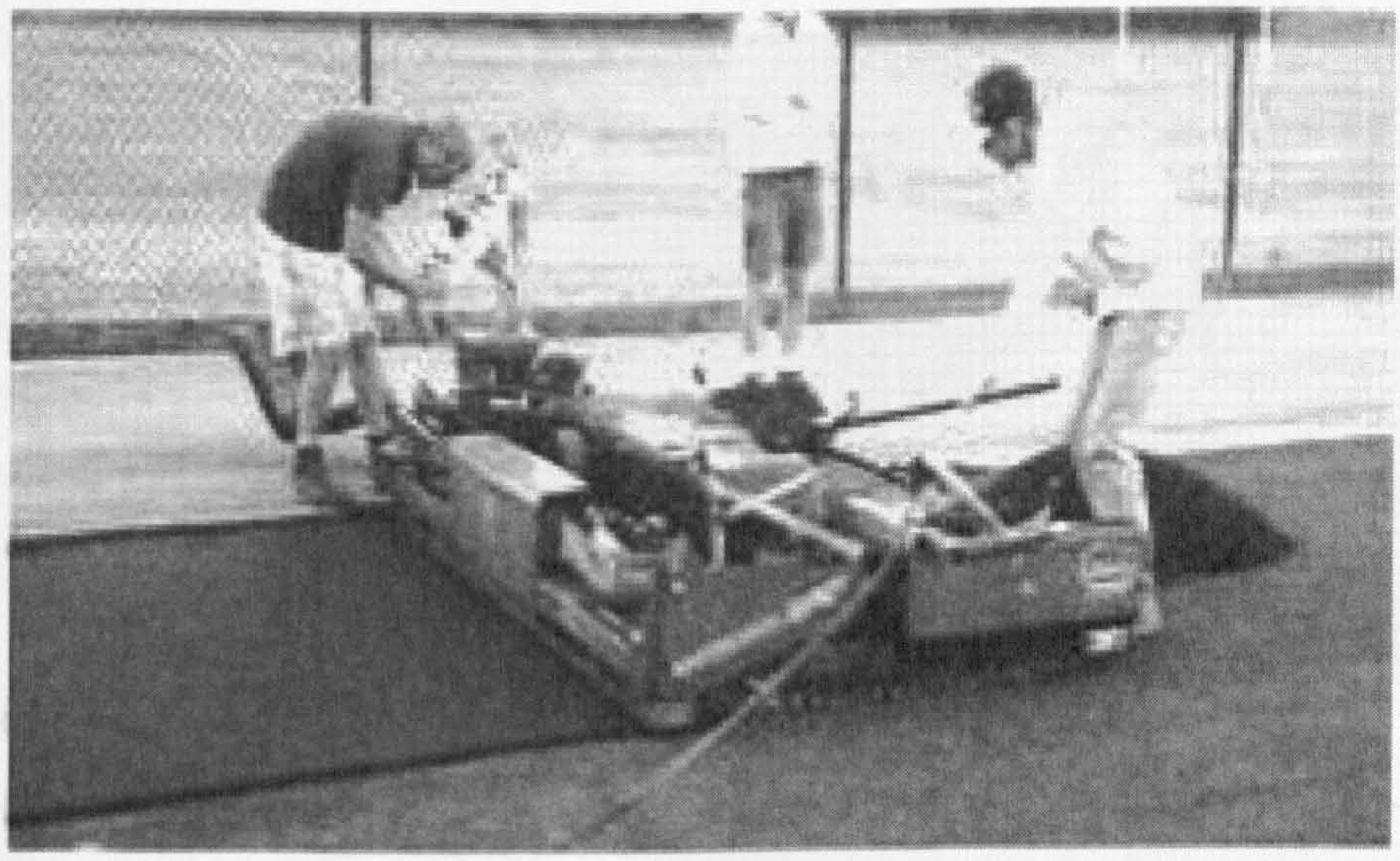


Figure 2.6: Oscillating levelling beam compacting rubber-polyurethane mix to produce a shockpad.

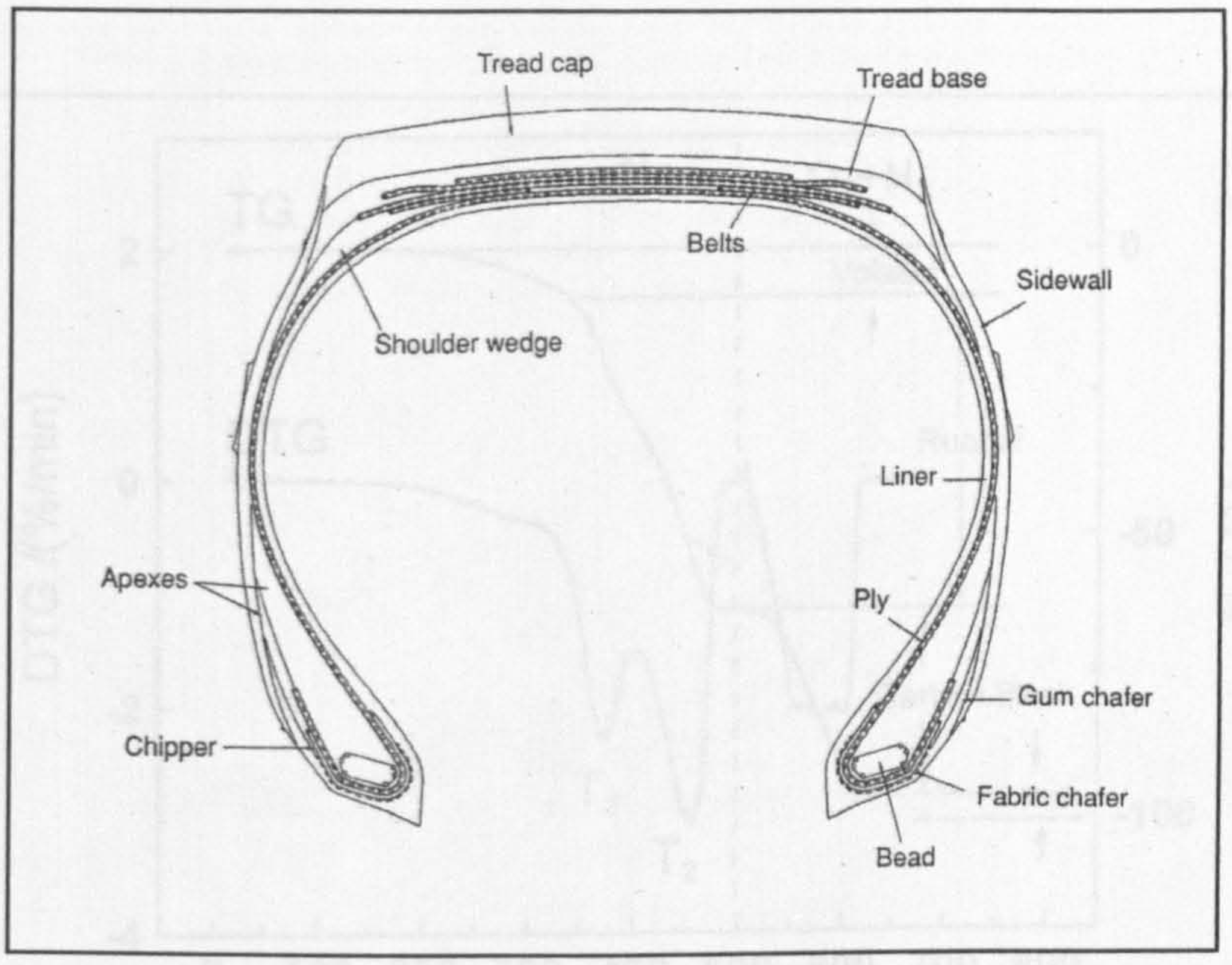


Figure 2.7: Cross section of a truck tyre. (Kovac and Rodgers, 1994)

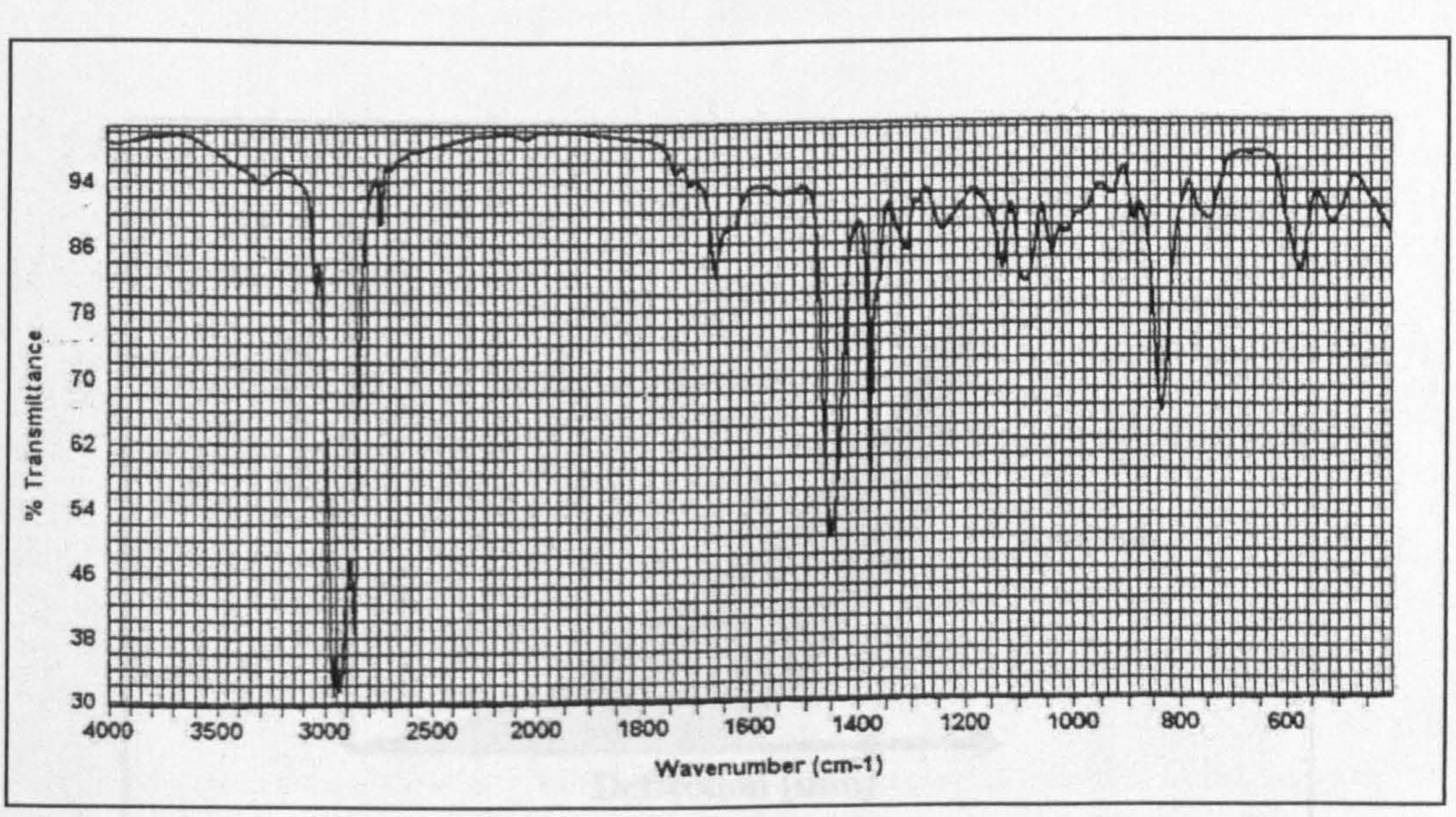


Figure 2.8: FTIR spectrum for Natural Rubber (Forrest, 2001)

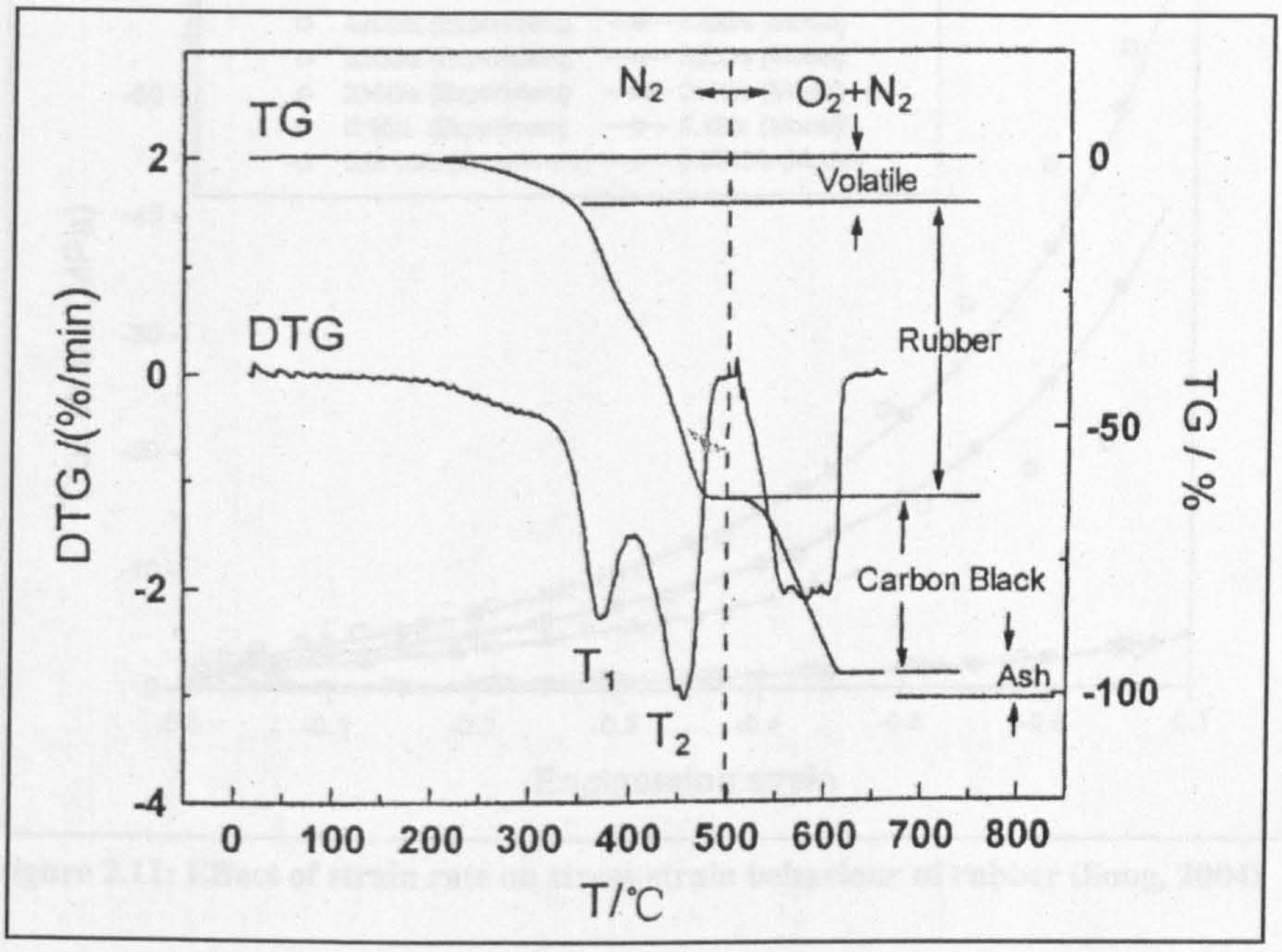


Figure 2.9: TGA and DTGA spectrum for a rubber sample taken from a tyre (Cui et al, 1999)

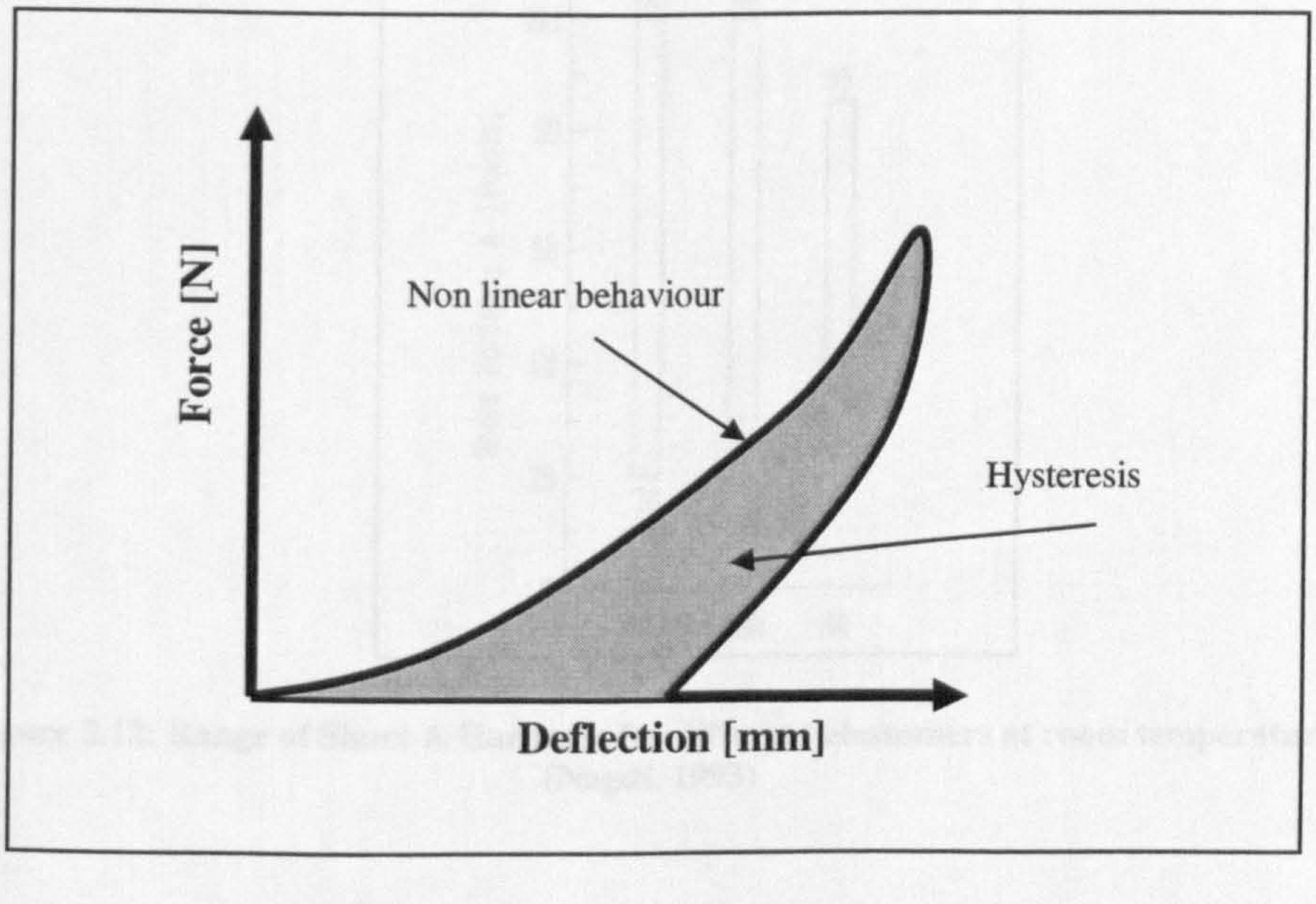


Figure 2.10: Compressive behaviour of rubber

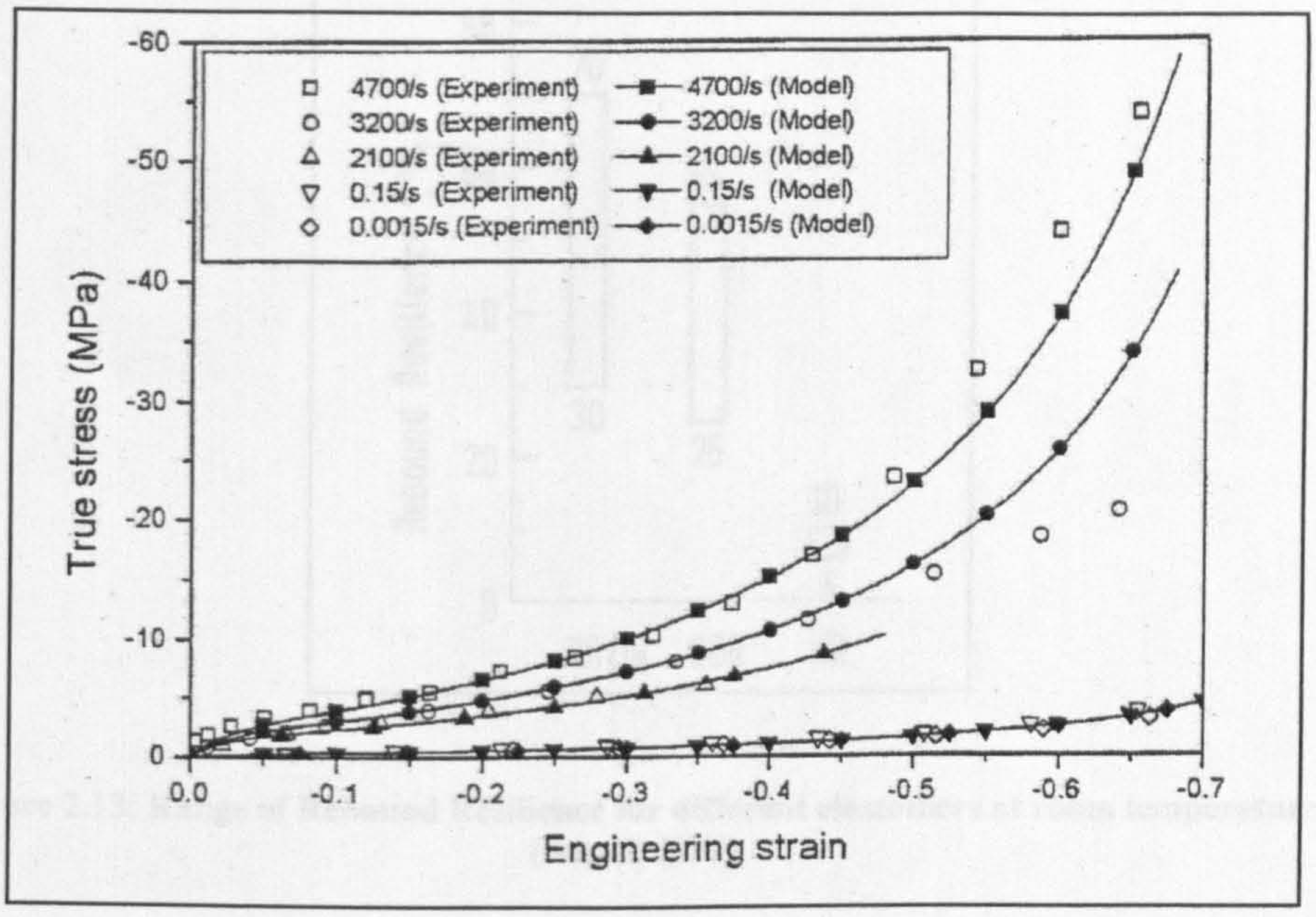


Figure 2.11: Effect of strain rate on stress-strain behaviour of rubber (Song, 2004)

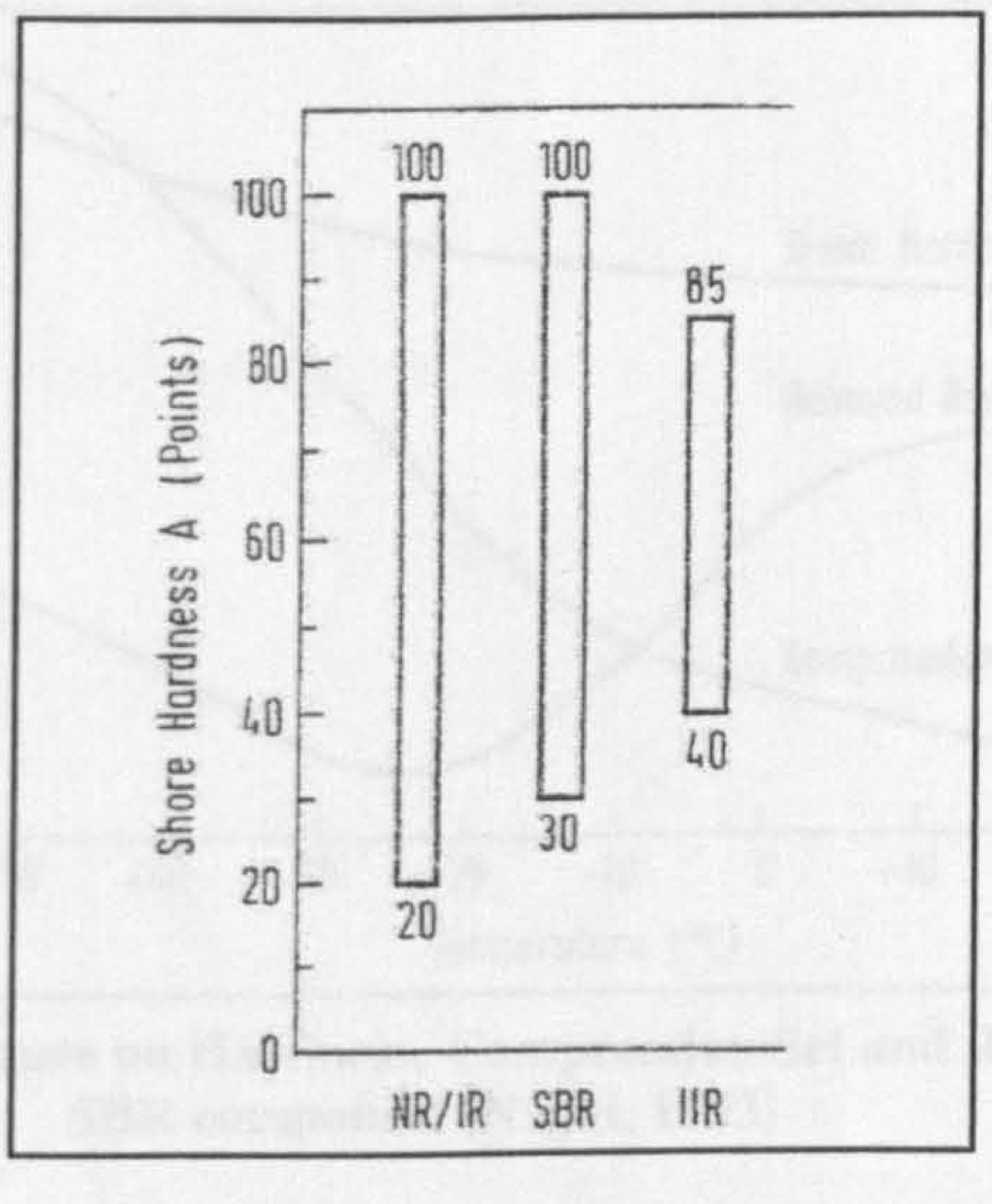


Figure 2.12: Range of Shore A Hardness for different elastomers at room temperature (Nagdi, 1993)

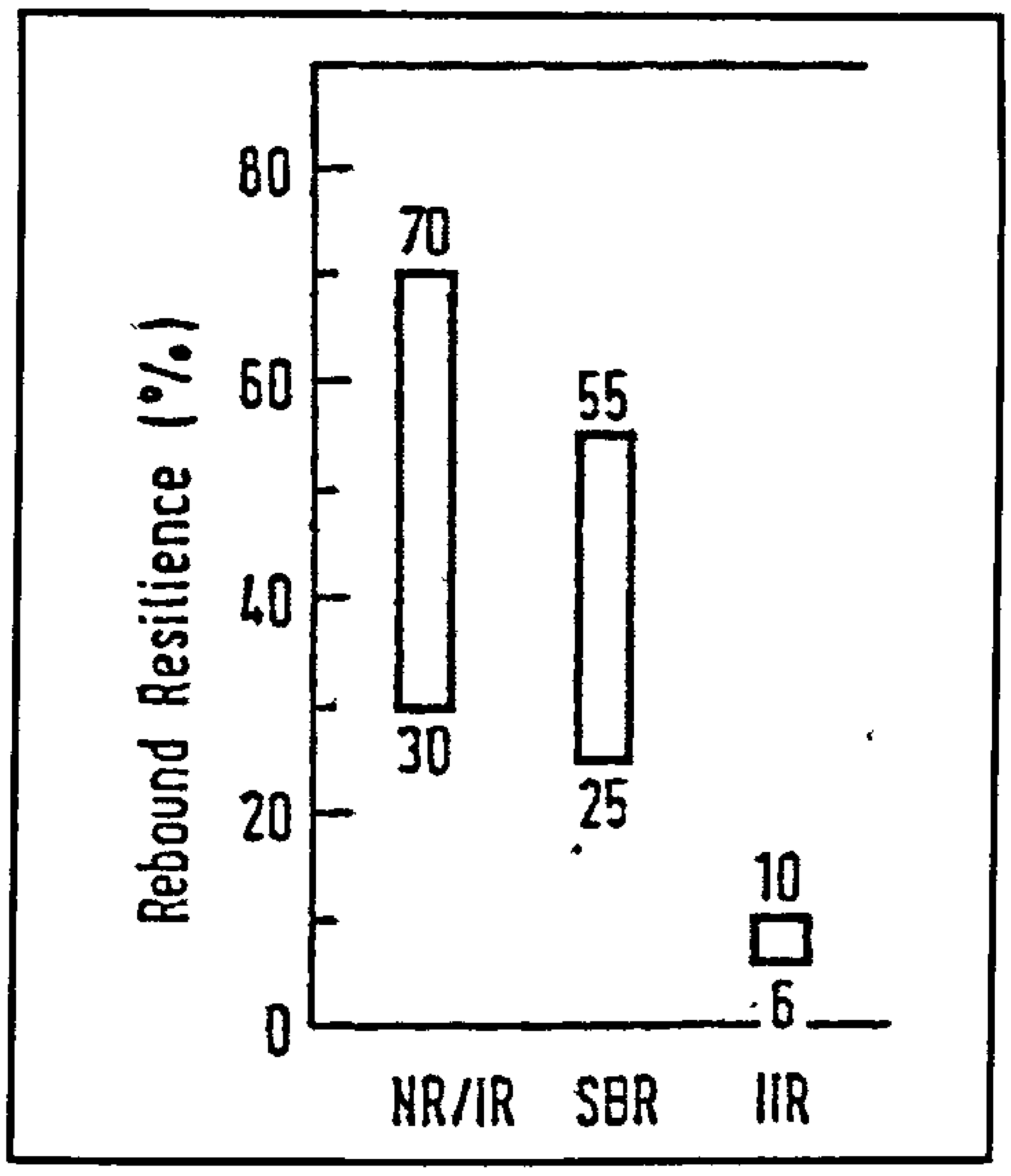


Figure 2.13: Range of Rebound Resilience for different elastomers at room temperature (Nagdi, 1993)

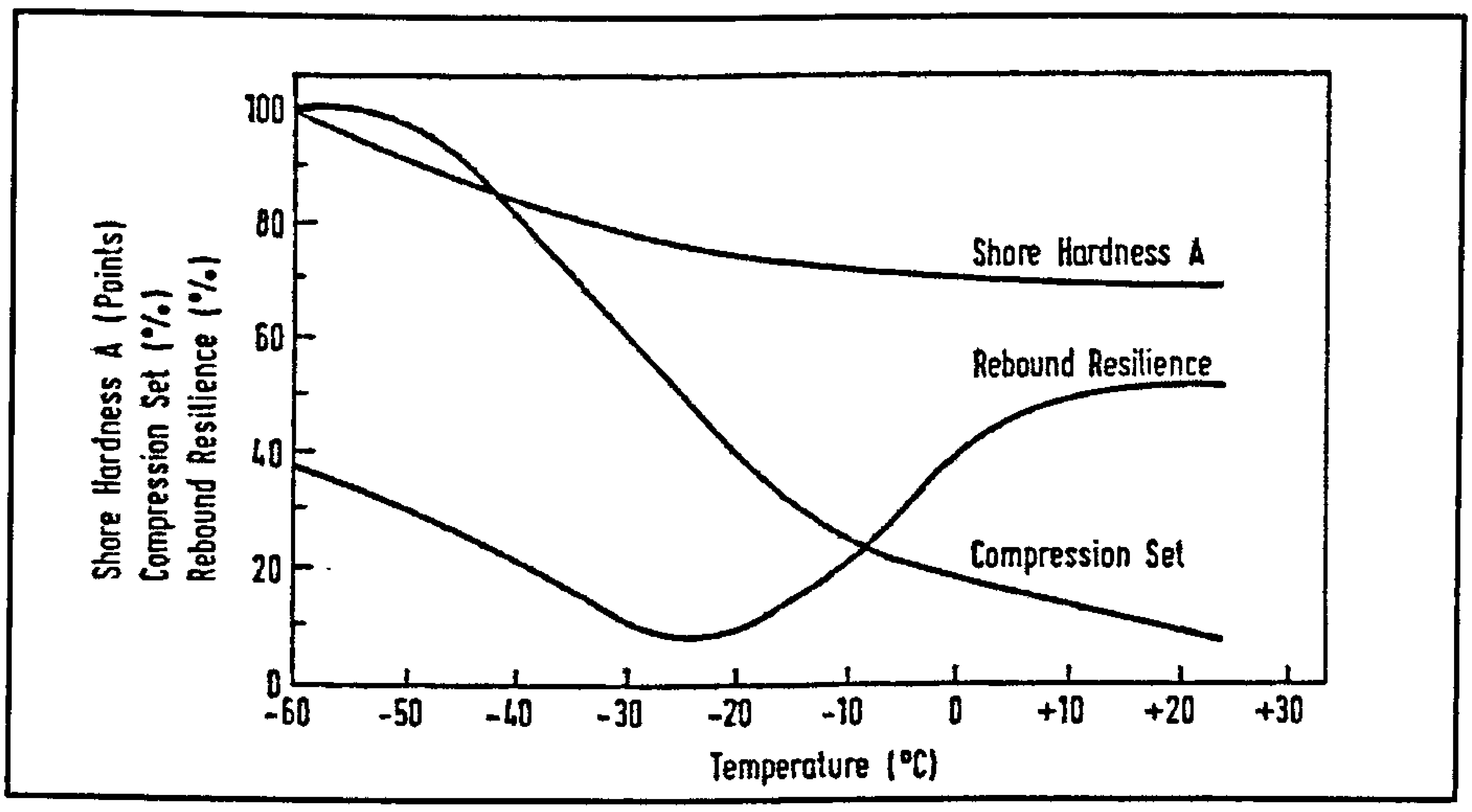


Figure 2.14: Effect of temperature on Hardness, Compression Set and Rebound Resilience of an SBR compound (Nagdi, 1993)

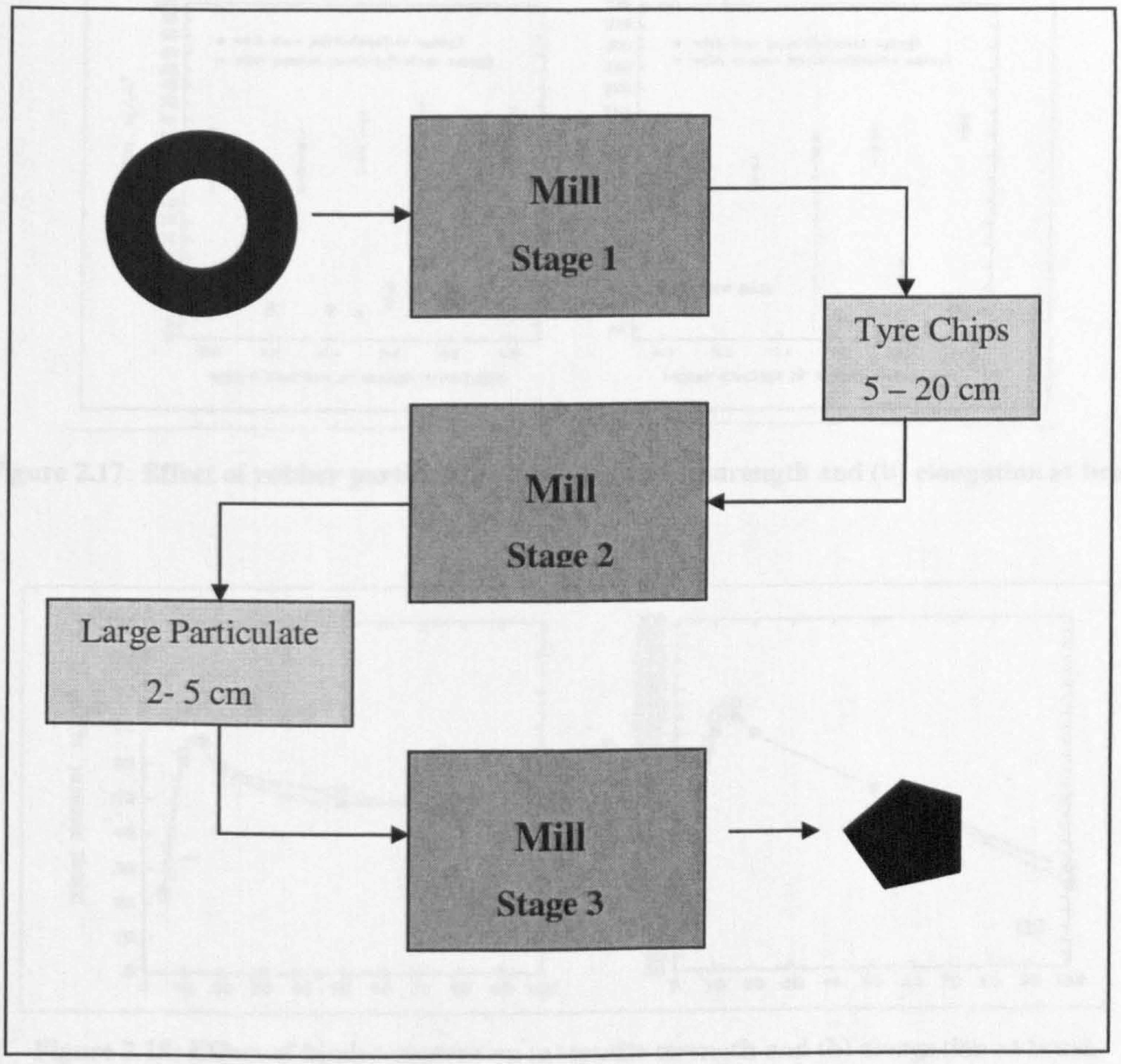


Figure 2.15: Stages of ambient ground method of the tyre recycling process

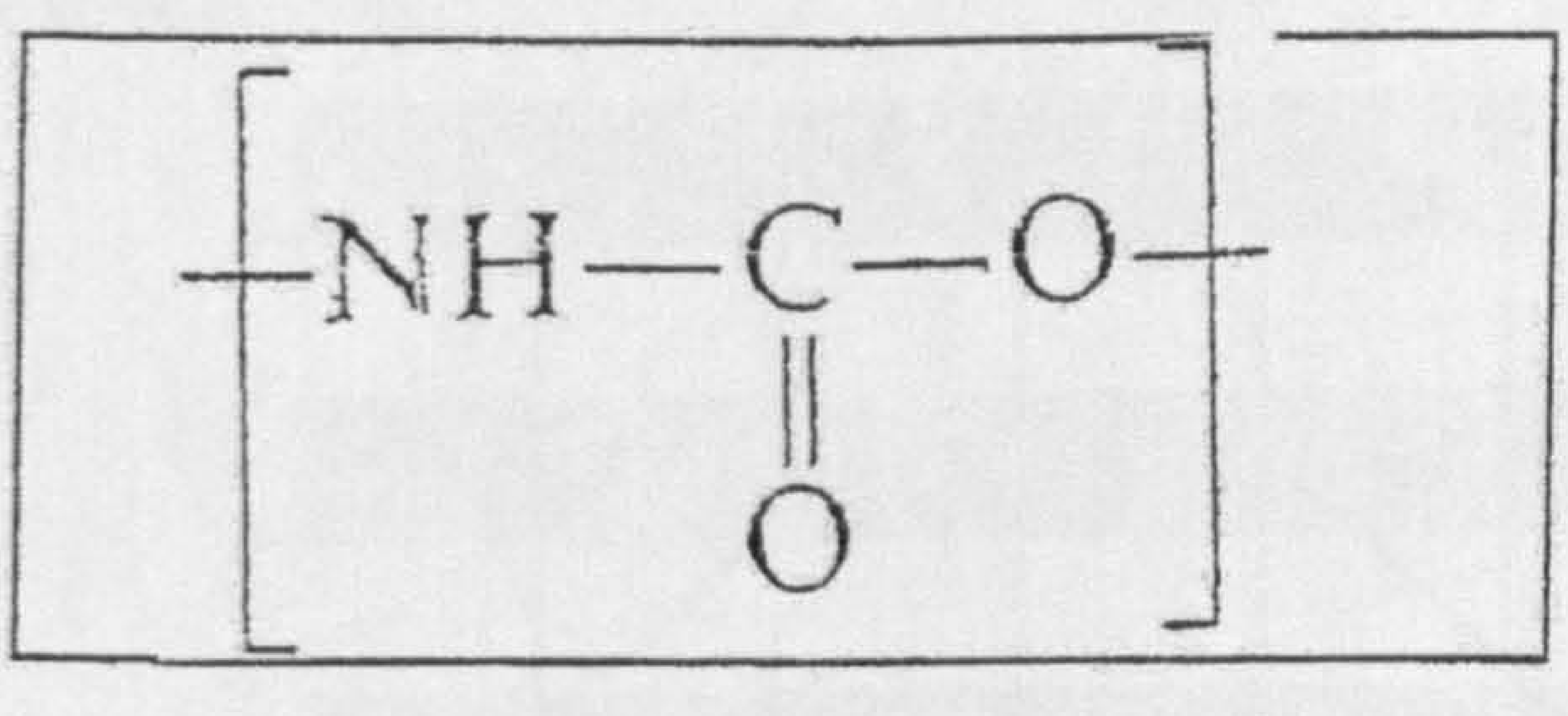


Figure 2.16: Urethane linkage in a polymer chain (Wake, 1982)

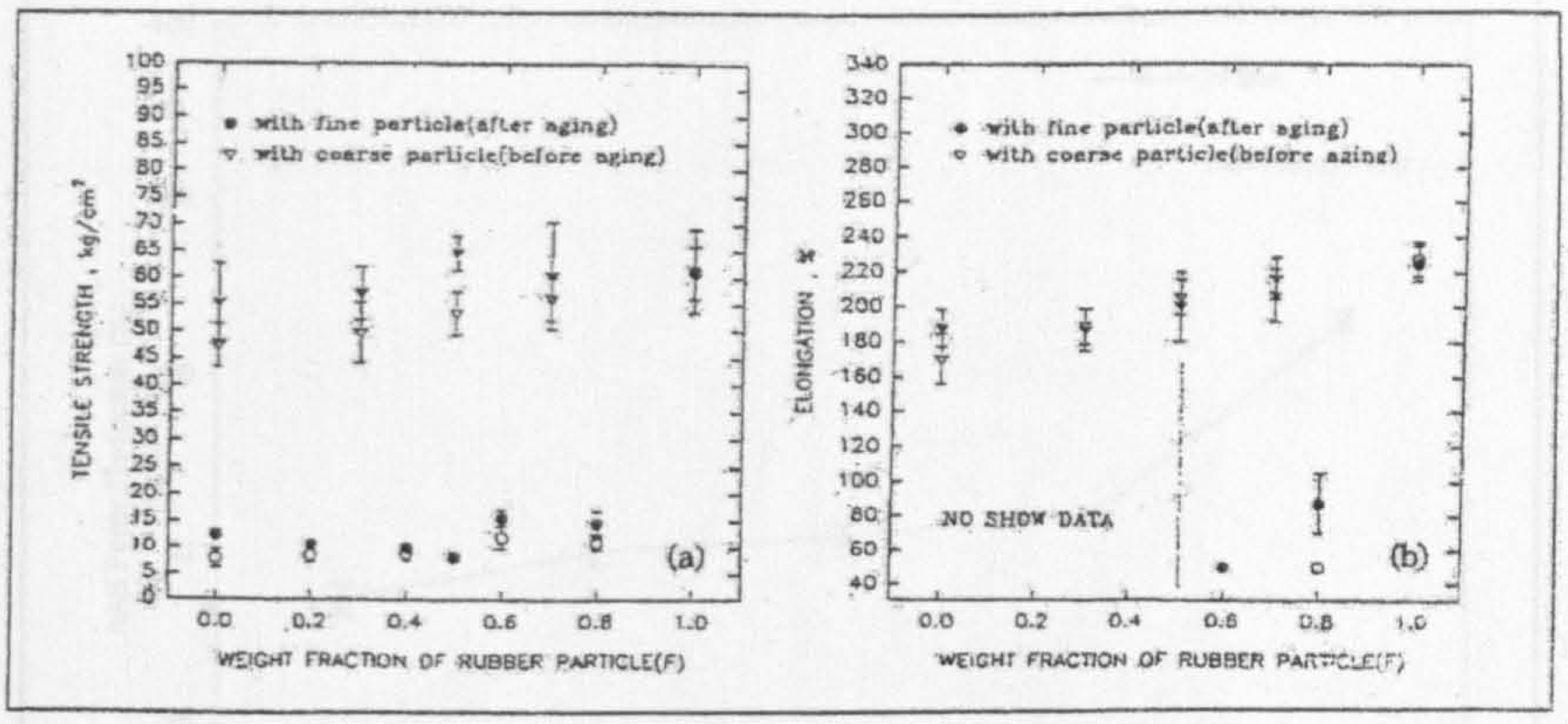


Figure 2.17: Effect of rubber particulate size on (a) tensile strength and (b) elongation at break (Kim, 1997)

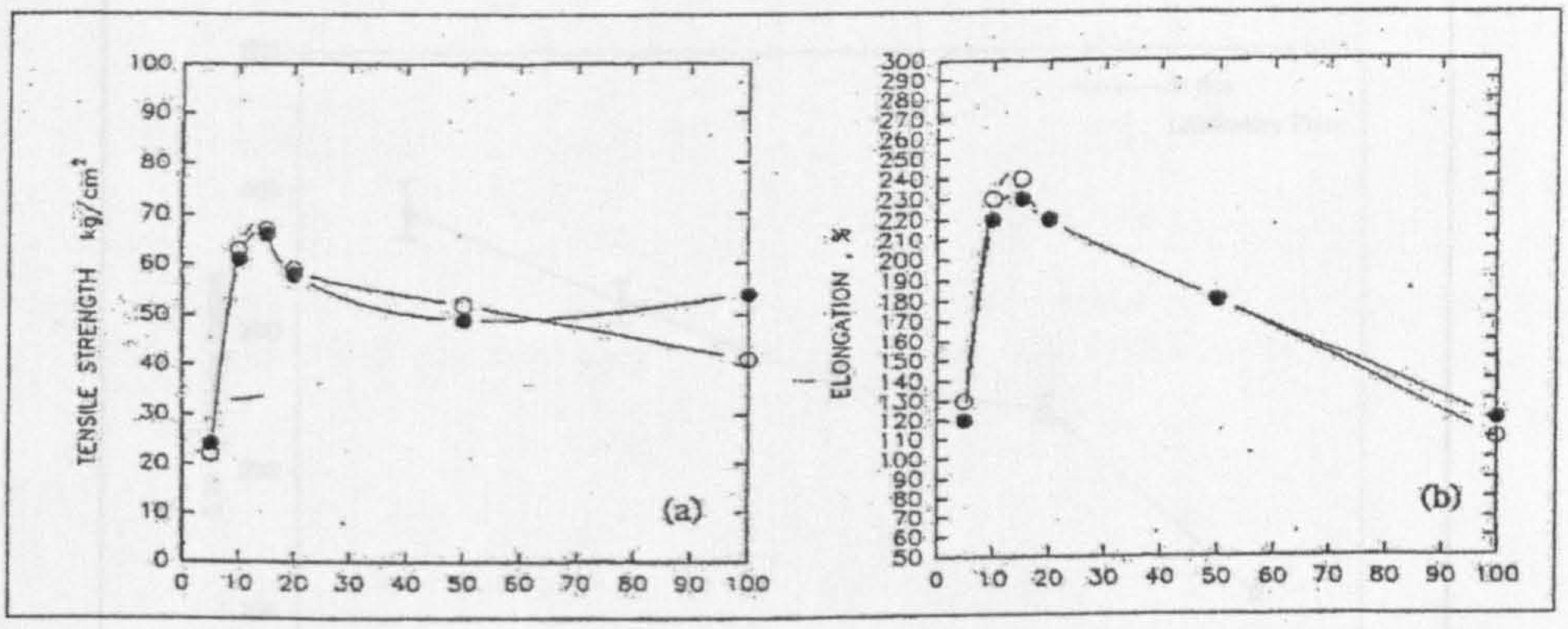


Figure 2.18: Effect of binder content on (a) tensile strength and (b) elongation at break (Kim, 1997)

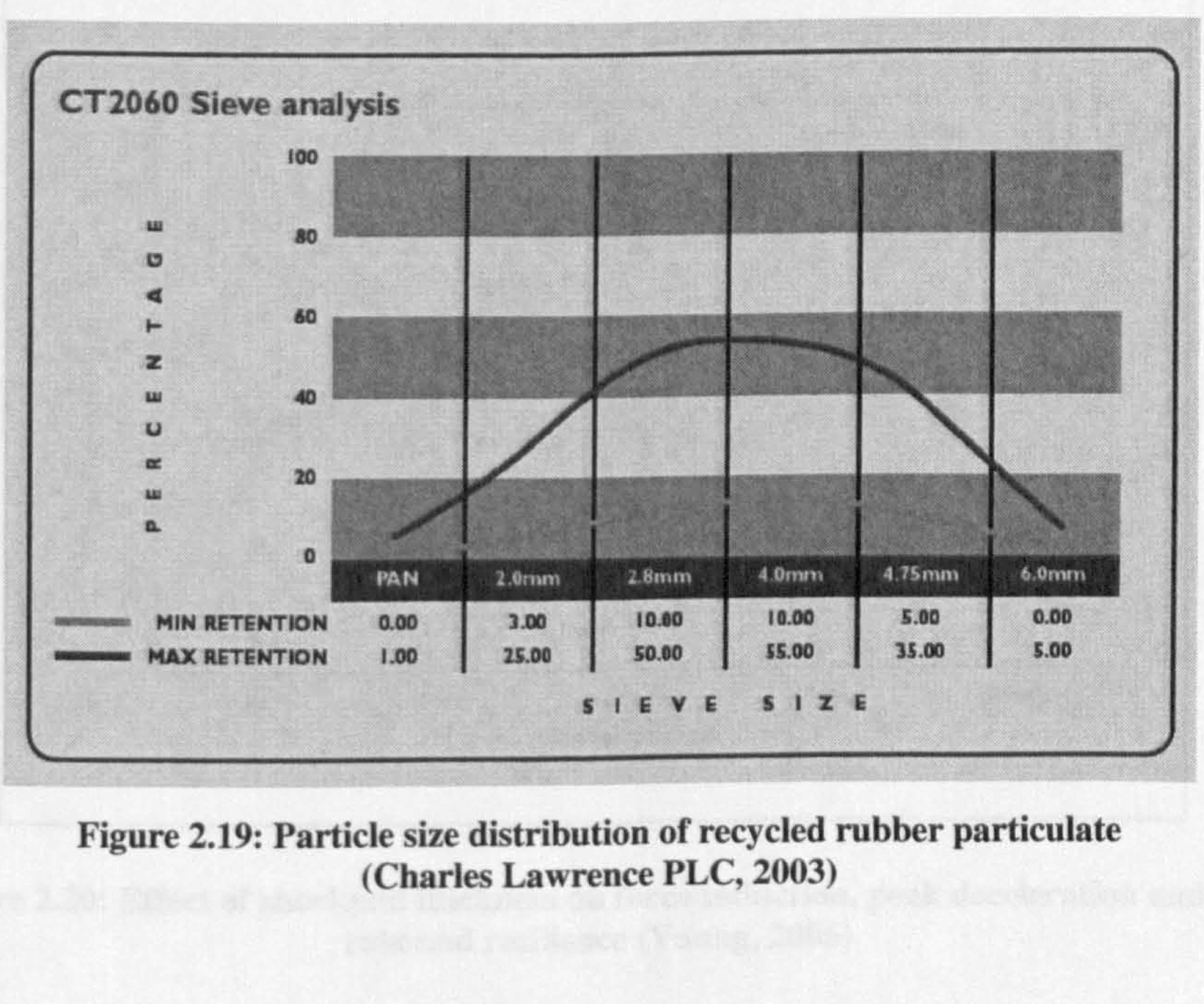


Figure 2.19: Particle size distribution of recycled rubber particulate (Charles Lawrence PLC, 2003)

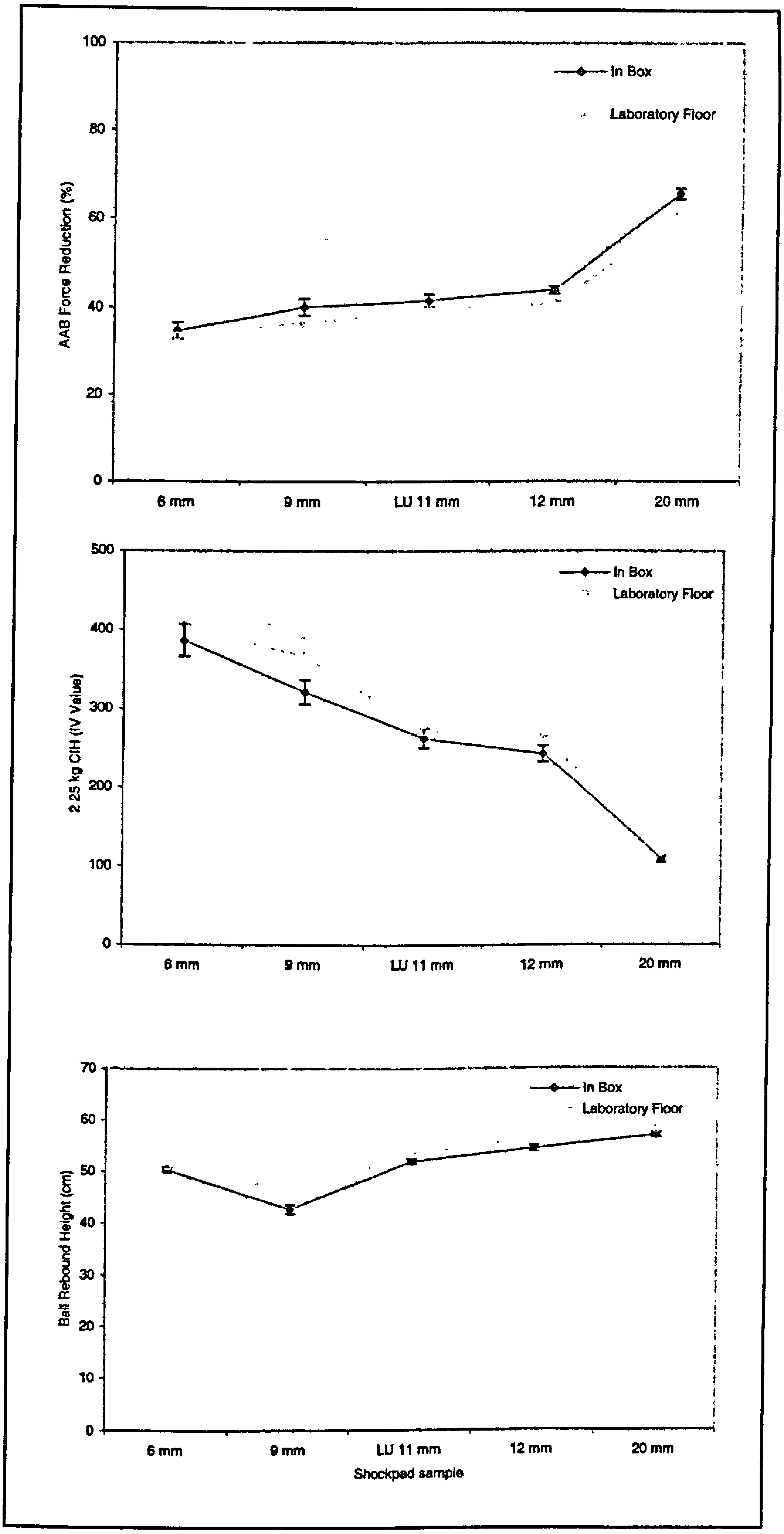


Figure 2.20: Effect of shockpad thickness on force reduction, peak deceleration and ball rebound resilience (Young, 2006)

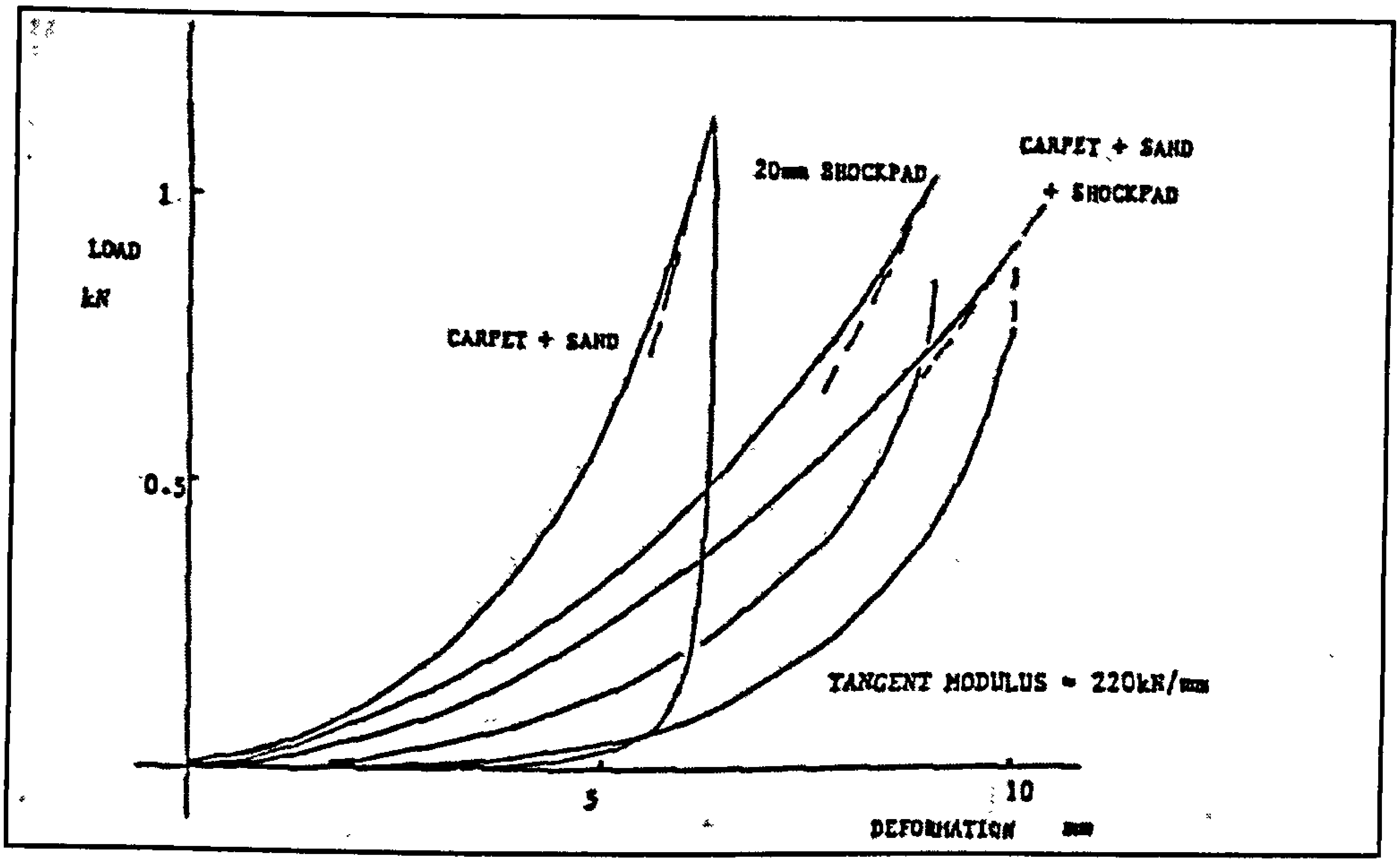


Figure 2.21: Force-displacement behaviour of quasi-statically loaded sand filled carpet, 20 mm shockpad and combined carpet-shockpad system (Walker, 1996)

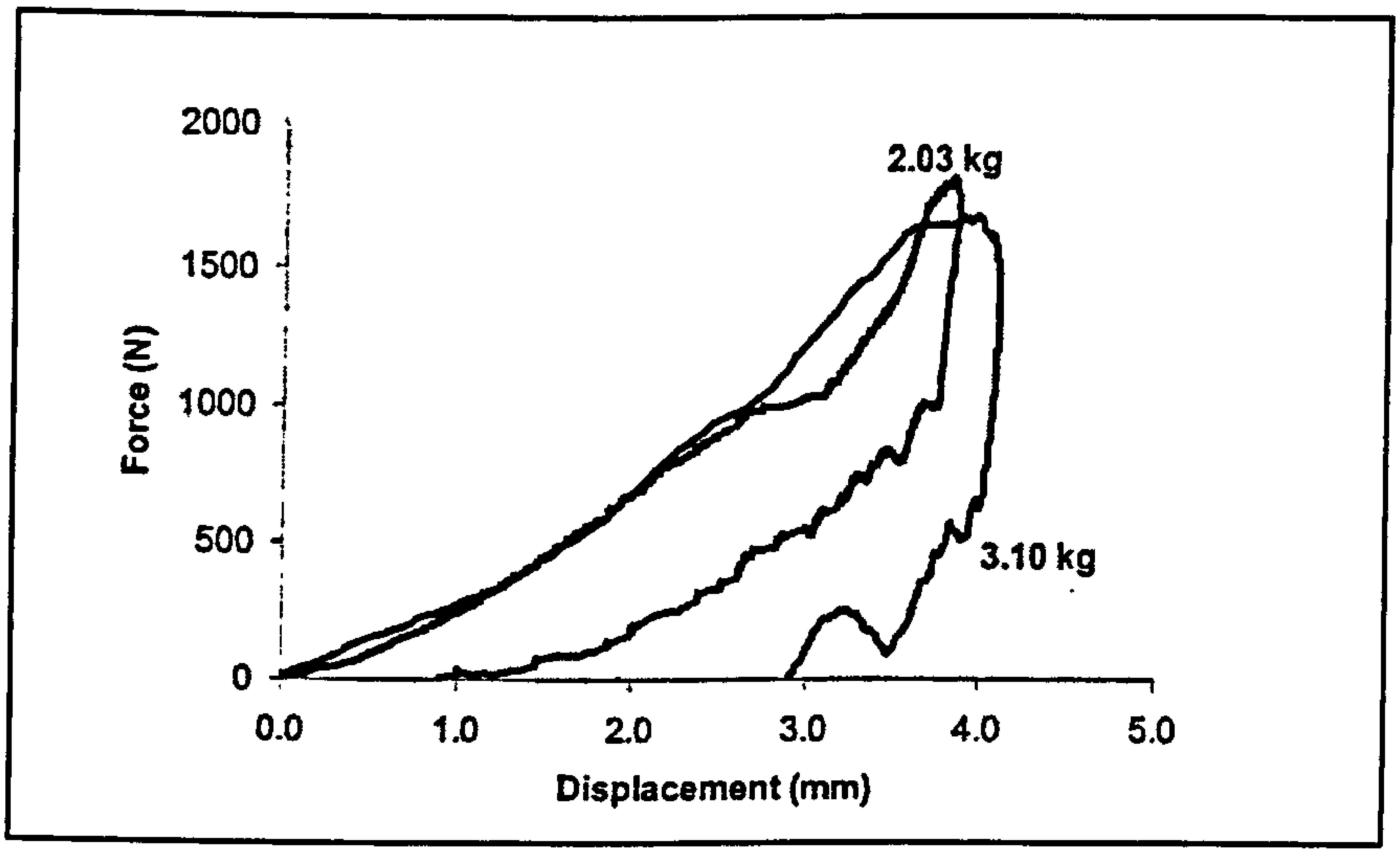


Figure 2.22: Force-displacement behaviour of a bound rubber particulate athletics track (Carré et al, 2004)

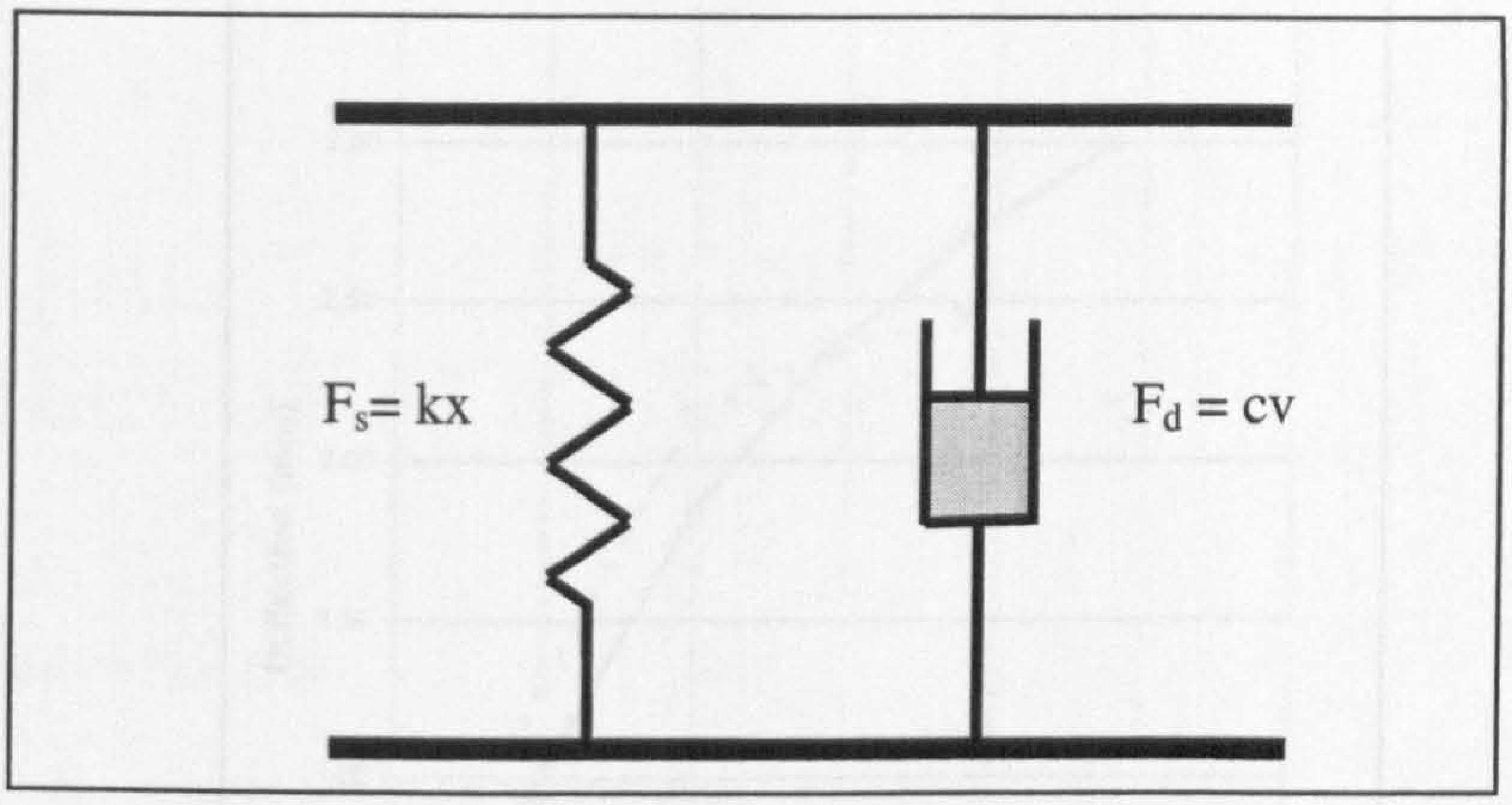


Figure 2.23: Kelvin-Voight model for elastomeric materials

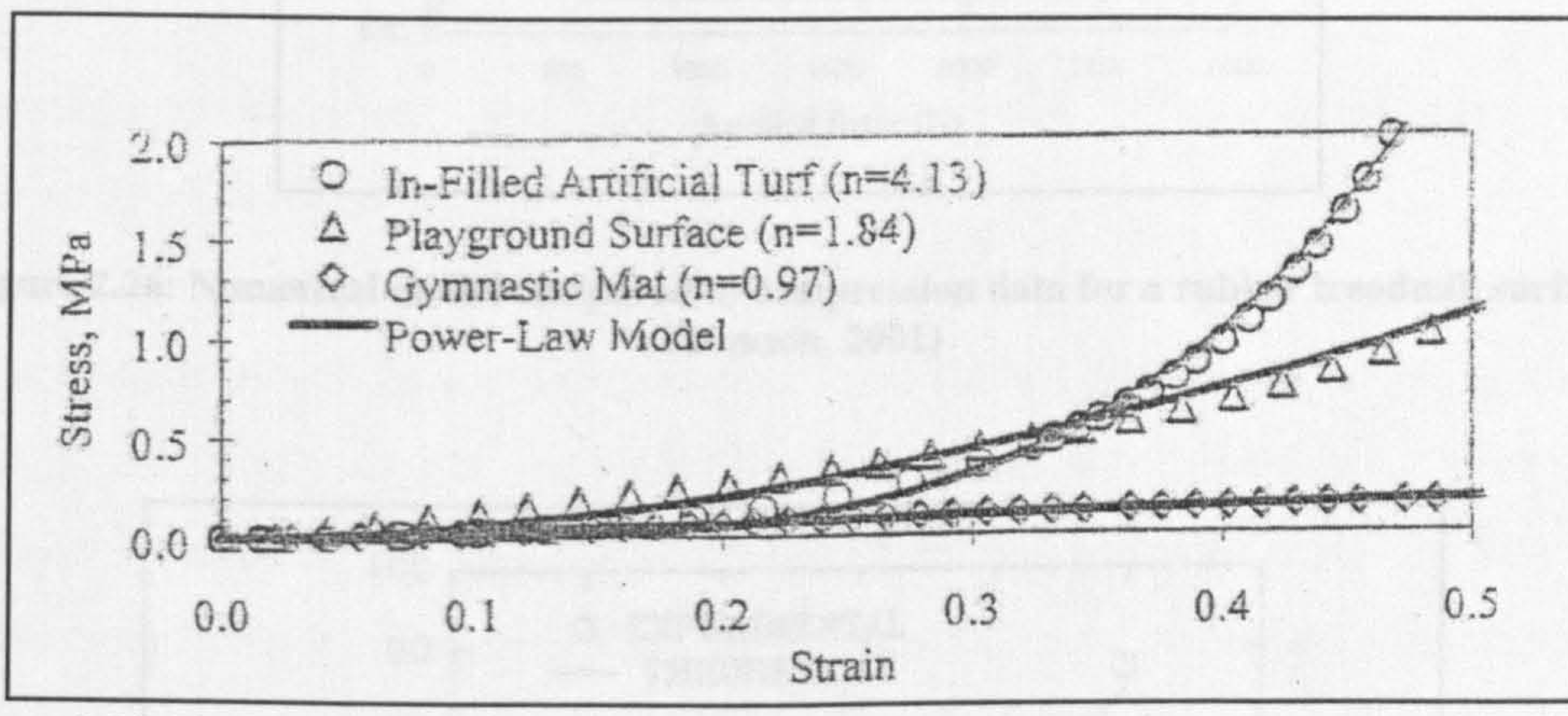


Figure 2.24: Variable non-linear model applied to playground surface, gym mat and in-filled carpet (Shorten and Himmelsbach (2002)

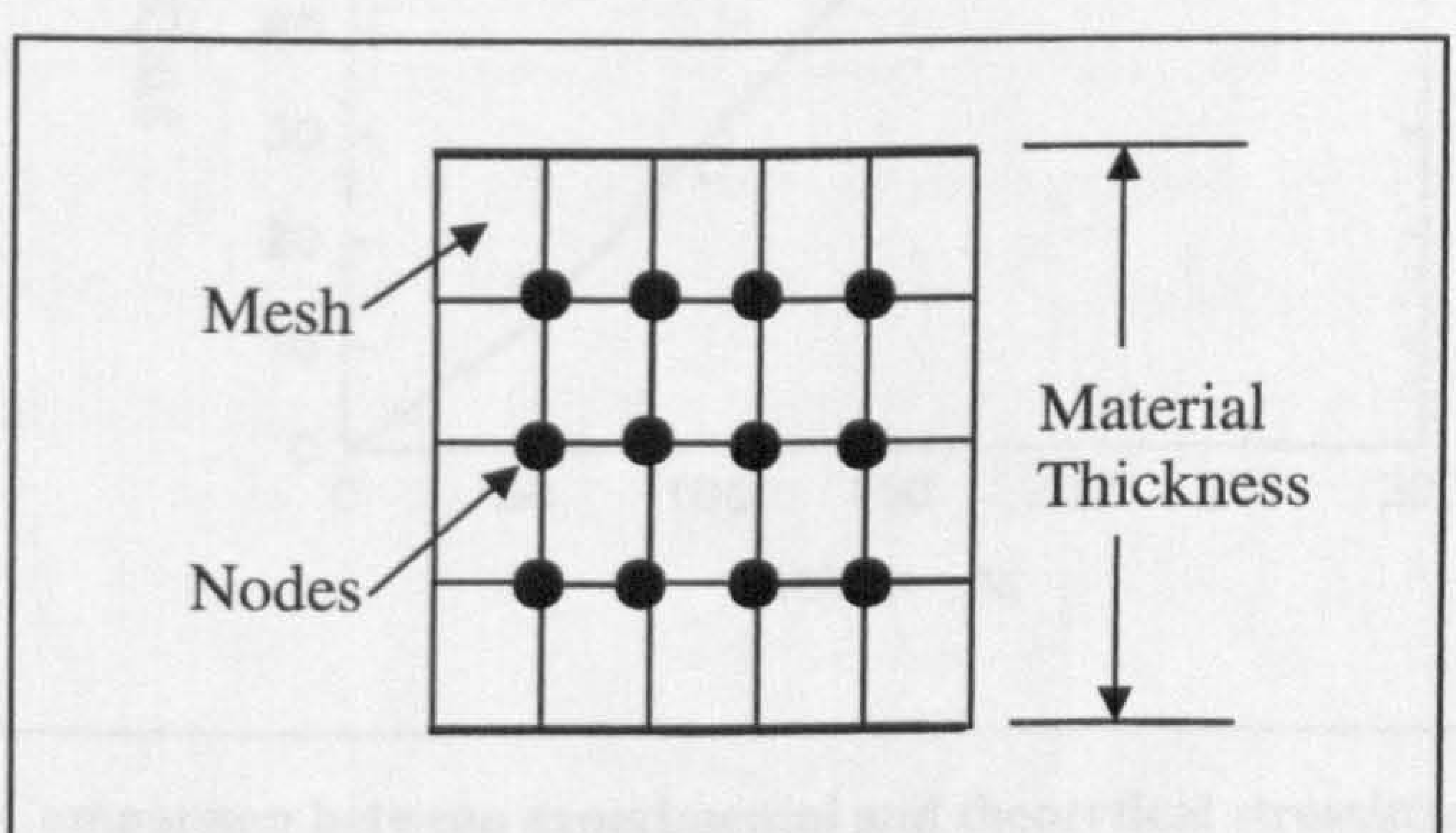


Figure 2.25: Method of numerical modelling using mesh and node points

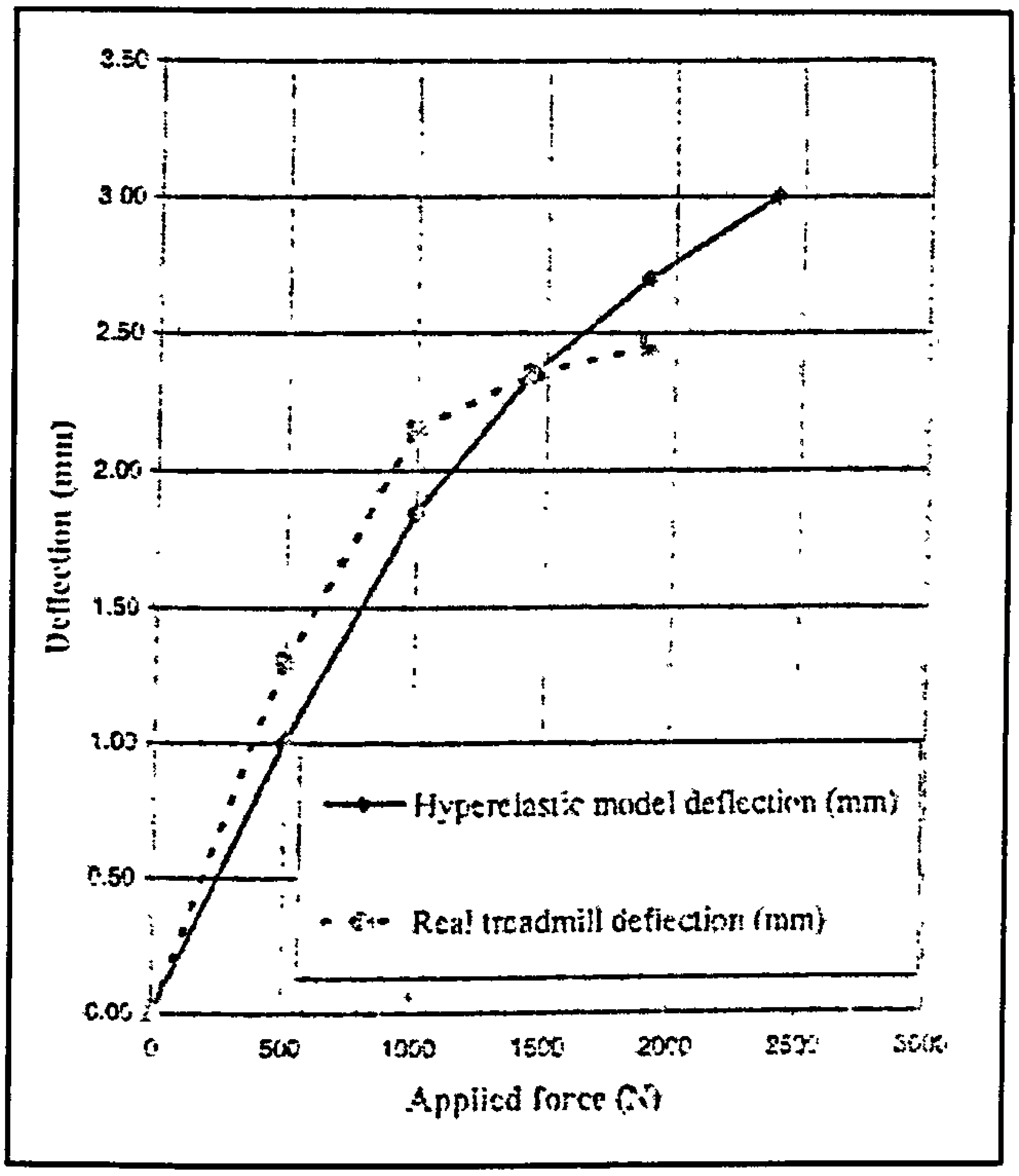


Figure 2.26: Numerical model compared to compression data for a rubber treadmill surface (Thomson, 2001)

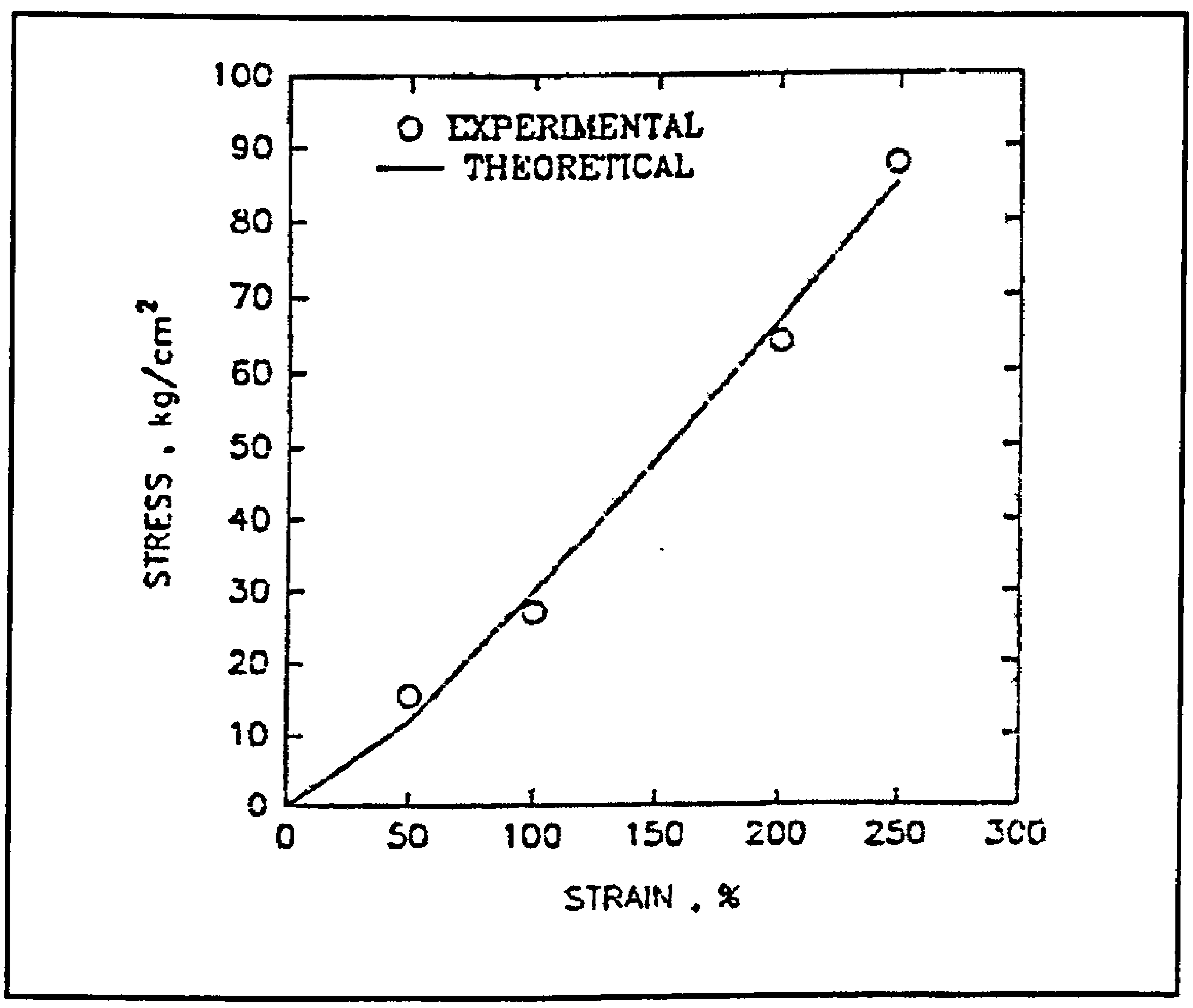


Figure 2.27: Comparison between experimental and theoretical stress/strain behaviour of a rubber particulate/PU blend (Kim, 1997)

Chapter 3

CHARACTERISATION OF RECYCLED RUBBER PARTICULATE

3.1 Introduction

Cast in-situ shockpads are composite structures, composed of recycled rubber particulate bound in a polyurethane resin. The mechanical properties and behaviour of shockpads are a product of the individual constituent material properties, their relative proportions and the design in which they are combined. Therefore, understanding shockpad mechanical properties and behaviour requires some knowledge of its components.

In the context of this thesis, the term 'recycled rubber particulate' refers to rubber particulate derived from post-consumer truck tyres and not rubber derived from other recycling streams such as door seals, trim or granulated virgin rubber. The literature review of recycled rubber particulate provided insufficient published information to determine its composition and physical and mechanical properties. The particulate was shown to be a mix of rubber compounds used to manufacture different sections of truck tyres. Designs for truck tyres, such as the proportions of tyre sections and the composition and properties of each section have not been published for commercial reasons. Recycled rubber particulate was therefore identified as having the potential to be a variable product that could influence the mechanical properties and behaviour it is used to construct, and therefore requires characterisation to determine the extent of potential variations in shockpad constructed in this research project due to rubber composition.

Polyurethane binders, unlike recycled rubber particulate, are formulated and manufactured specifically for the purposes of shockpad manufacture and are uniform in composition. Some published mechanical and physical property data was identified from literature and these properties are routinely tested for quality control purposes. Polyurethanes are manufactured using precisely measured quantities under controlled conditions and were therefore not considered to be a variable product requiring detailed characterisation. The effects of cure time and binder type on shockpad mechanical properties are examined as mix design variables in Chapter 4 of this thesis.

This chapter focuses on characterising recycled rubber particulate used in shockpad constructions in terms of its composition and its subsequent physical and mechanical properties. The thesis, as a whole, focuses on the cast in-situ variety of shockpad, however the recycled rubber particulate is common to prefabricated shockpads and other bound rubber particulate surfaces for playgrounds and walkways. This findings of this chapter are therefore also applicable to recycled rubber particulate used for these structures.

Rubber variables identified in the literature review as having the potential to influence the mechanical properties of the shockpads it was used to produce include rubber shape, composition, size range and size distribution. The use of recycled rubber particulate from various manufacturers to examine the effects of all rubber variables on shockpad mechanical properties would require an in-depth study of the feedstock and output products of the recycling process to characterise the similarities and differences. Such a study would constitute a project within itself and is therefore not within the scope of this thesis.

The effect of rubber composition on the mechanical properties and behaviour of shockpads could be controlled in two ways. Firstly, a uniform batch of rubber could be obtained or manufactured and granulated (although difficult for a small batch) to form rubber particulate. This rubber would not have the same composition as that obtained from truck tyres and therefore would not exhibit the same mechanical properties. Mechanical property and behavioural data obtained from testing shockpads constructing using the uniform rubber would subsequently be of limited value to the shockpad construction industry.

The second method used a batch of recycled rubber particulate supplied by one major producer to construct all shockpads used in Chapters 4 and 5 of this research project.

This was the preferred method as findings for characterising rubber particulate, shockpad mechanical properties and behaviour could be directly used by the sports surfacing industry. This decision controlled rubber shape since the same processing method was used for the whole batch, but allowed rubber size range and size distribution to be examined as mix design variables in Chapter 4. However, as the composition of the supplied recycled rubber particulate was not required to be supplied with the rubber, the potential for rubber composition variations identified in the literature review and its subsequent effect of the physical and mechanical properties of the rubber remained unknown. The effect of rubber compositional variations was required to be minimal for this method to be acceptable for the construction of shockpads, as it may otherwise affect mechanical property measurements for mix design variations made in Chapter 4.

The characterisation of composition and physical and mechanical properties of the supplied batch of rubber particulate involved the calculation of major truck tyre section mass based on dimensional measurements of the tyre feedstock. The composition and physical properties of each section were measured and compared with respect to the proportion of each section within the particulate, and the potential rubber composition to affect shockpad behaviour assessed. Two test methods, gyratory compaction and vertical compression, were developed to measure the mechanical properties of samples of rubber particulate as sample sizes obtained from truck tyre sections prevented well established mechanical property tests from being conducted. The following sections detail the methodologies undertaken, the results of characterisation and a discussion of the variability within the supplied batch of recycled rubber particulate.

3.2 Experimental Methodology

3.2.1 Introduction

Rubber size range, rubber size distribution, rubber composition, rubber shape and rubber cleanliness were identified in the literature review as variables with the potential to influence the mechanical properties and behaviour of shockpads. However, rubber particulate used for the construction of shockpads is only classified as typically being sourced from granulated truck tyres and in the size range of 2-6 mm. This lack of characterisation was attributed to the few test methods and performance requirements stipulated by sporting governing bodies or in construction contracts for constituent materials.

Characterising rubber size range, size distribution, composition, cleanliness and shape for recycled rubber particulate produced by various suppliers in the UK would involve a detailed study that is not within the scope of this thesis. Therefore, to control variations in shockpads due to the rubber particulate used to produce them, one batch of rubber was selected from one leading particulate producer in the UK to be used to construct all shockpads as part of this research project. Using only one batch of rubber led to rubber cleanliness and shape being controlled, but rubber size range and size distribution could be varied by sieving the particulate and recreating various size ranges and distributions. The effects of rubber size range and size distribution on shockpad mechanical properties are examined in Chapter 4.

Rubber composition could not be controlled by using only one source of recycled rubber particulate. The literature review described the composition of recycled rubber particulate used to produce shockpads as a mix of the various rubber compounds contained within truck tyres. Truck tyres are constructed using various rubber compounds for each tyre section according to its function; however there was a lack of detailed published information regarding the composition or mechanical or physical properties of each section for commercial reasons. Rubber compounds were shown to be composed of rubber hydrocarbons, carbon black, extender oils and plasticisers and inorganic fillers. The proportion of each component contained in the rubber compound was shown to influence the physical and mechanical properties of the rubber it produced.

The determination of the various proportions of each component for various recycled rubber particulate products were reviewed, however the majority of products contained rubber from other sources such as natural rubber conveyer belts or only selected sections of a tyre such as the tread which influenced overall composition. The mix of various rubber compounds contained in the batch of rubber particulate was shown to have the potential to influence the mechanical properties of the shockpads it is used to produce. The literature review was not able to conclusively identify the composition of recycled rubber particulate and quantify its effect on the mechanical properties of shockpads it is used to produce.

Test methods are outlined in pr BS EN 14243:2002; a draft standard which is currently under development to characterise recycled rubber products. The standard identifies compositional analysis to be conducted by Thermogravimetric Analysis (TGA) but lacks physical and mechanical tests that can be conducted on samples as small as recycled rubber particulate. In addition, performing compositional analysis and physical and mechanical tests on a representative sample of randomly selected portion of particulate was not achievable as testing only 1% of the 500 kg batch supplied for shockpad construction would require approximately 65 000 tests. Alternatively, the recycled rubber particulate was characterised by an assessment of the tyre feedstock to reduce the number of tests to a reasonable quantity and to ensure all tyre sections used to produce the rubber particulate were adequately represented.

A test programme was developed to characterise the supplied batch of recycled rubber particulate in terms of composition and physical and mechanical properties and assess the potential for variations to affect shockpad properties using the method outlined in Figure 3.1. The programme involved dividing the truck tyre into the major sections identified in the literature review and estimating the mass of each section by taking measurements of truck tyres from the feedstock. Samples of each major tyre section were taken from the granulation process and used to conduct compositional and physical property tests. Tyre section samples were not large enough to conduct mechanical property tests, and in the absence of a suitable compressional mechanical property test for rubber particulate, a test was devised for small batches of particulate. The results of the testing were used to assess the potential for the batch of recycled rubber to influence the mechanical properties and behaviour of the shockpads it was used to produce.

The steps taken to determine the constitution of the typical batch in terms of major tyre sections and physical, mechanical and compositional tests to determine its variability are outlined in the following sections.

3.2.2 Tyre Dimensional Measurements

The four major sections of a truck tyre were identified in the literature review as being the tread, sidewall, inner liner and apex, with smaller components being the gum chafer and wire skim (Bennett, 2005). The volume of each major tyre section was approximated by separating the tyre into these major sections as shown in Figure 3.2 and applying Equations 3.1 to 3.4.

Tread: $T_v = T_d \times T_w \times C_o$ ------- Equation 3.1

Sidewall: $S_v = 2 \times S_t \times S_a$ ------- Equation 3.2

Inner Liner: $I_v = I_w \times I_t \times I_c$ -------- Equation 3.3

Apex: $A_v = 2 \times A_a \times C_b$ -------- Equation 3.4

Where:

T_v	=	Tread Volume	[m³]
T_d	=	Tread Depth	[m]
T_w	=	Tread Width	[m]
C_o	=	Outer Circumference	[m]
S_v	=	Sidewall Volume	[m³]
S_t	=	Sidewall Thickness	[m]
S_a	=	Sidewall Area	[m²]
I_v	=	Inner liner Volume	[m³]
I_w	=	Inner liner Width	[m]
I_t	=	Inner liner Thickness	[m]
I_c	=	Inner Circumference	[m]
A_v	=	Apex Volume	[m³]
A_a	=	Apex Cross Section Area	[m²]
C_b	=	Bead Circumference	[m]

The volume of the tread section, estimated by Equation 3.1, assumed the tyre to be cut through the one half of its cross section and was extended to lay flat to form a rectangle as shown in Figure 3.2. Length of the rectangular section was the same as the circumference measured around the tyre and width of the tread measured by the shoulder to shoulder distance. Vertical height was determined by the tread depth measured down to the tyre shoulder. Tread depth, and therefore tread volume, may vary depending on the amount of tyre wear. The particulate supplier indicated most tyres in the particulate feedstock were post-consumer truck tyres with maximum allowable wear. It was therefore assumed most tyres would be discarded with a consistent tread depth.

Sidewall volume was approximated by two circular disks either side of the tyre, given by Equation 3.2. The diameter of disk's outer circle was given as the shoulder to shoulder measurement and the inner diameter as the distance from bead to bead as shown in Figure 3.2. Sidewall thickness was formed in a complex shape, and was estimated from taking an average of five measurements along five individual sidewall sections (outlined in Section 3.2.3) to provide an average of twenty five thickness measurements.

Inner liner volume was determined similarly to the tread and is given by Equation 3.3. The tyre was assumed to be cut through one half of its cross section and laid flat to form a rectangle, as shown in Figure 3.2. Width was determined by the measurement of bead to bead distance and the inner circumference of the tyre. Thickness of the inner liner was determined from an average of five measurements on each of five individual inner liner tyre sections (outlined in Section 3.2.3) to produce an average thickness from twenty five measurements.

The apex section of the tyre was encased within the tyre between the lower section of sidewall and inner liner and therefore could not be directly measured using whole tyres. The area of five apexes were measured from individual tyre sections containing the whole apex cross sections outlined in Section 3.2.3, and the average area determined. The cross sectional area of an apex was a complex shape, similar to that shown in Figure 3.2, which could not be estimated by applying basic geometry. It was therefore estimated by tracing the area onto 2 mm squared graph paper and calculating the number of squares contained within the area. The apex was continuous around the circumference of the tyre and the length of the section estimated by the circumference of the bead. Each tyre contained two apex sections behind each sidewall and the overall volume is given by Equation 3.4.

Initially, it was planned that the mass and dimensions for a sample of tyres from the feedstock would be measured and averages determined. However, two tyre sizes 295/80 R22.5 and 385/80 R22.5 were identified by the particulate supplier as being the predominant type of tyre feedstock, in a ratio of approximately 1 to 1. A survey of the feedstock pile proved this to be a correct assessment.

Two tyres (one of each size) were weighed to the nearest kilogram to determine mass. Dimensions required to determine the volume of each major tyre section were measured using a measuring tape. Each tyre was assumed to contain 30% (by mass) steel as wire reinforcements and the bead (Kumho, 2003; Continental Tyres, 1999) which was subtracted from the overall mass of the tyre to determine rubber mass. It was assumed that all of the rubber contained within a tyre was converted to particulate and the mass of dust produced and rubber remaining on the wire is negligible.

The volume of each section for each tyre was determined using Equations 3.1 to 3.4. The volume to rubber mass ratio was determined for each major tyre section and an average taken of the two values to give an average section volume per 100 kg mass of particulate produced. Density calculations for each tyre section, measured according to Section 3.2.5.1, were then used to convert average section volume to average section mass per 100 kg of rubber mass using Equation 3.5.

$$M_s = \rho_s \times V_s \quad \text{--------- Equation 3.5}$$

Where:

M_s	=	Section Mass	kg
ρ_s	=	Section Density	kg/m^3
V_s	=	Section Volume	m^3

3.2.3 Tyre Section Sampling

Samples of each major tyre section were collected from the first stage of the rubber particulate recycling process shown in Figure 2.15 Tyre sections were taken from this stage of the process as steel removal was easier than for whole tyres but were still large enough to identify the original location for each section. Five samples of each major tyre section were selected over a 30 minute time period of the continuously running process to statistically determine the range of physical properties and compositional variation exhibited for each tyre section and between different sections. For apex sections, only samples showing whole cross sections were selected as they were required for volume measurements.

Steel wire and beads were separated from the rubber for each sample using a hand saw to remove large steel sections and pliers to remove smaller steel wires. A razor blade was used to create samples with approximate dimensions of 20 by 20 by 10 mm. Sidewall and inner liner samples were 6 and 1.5 mm thick respectively due to thin sections contained on the tyre. Regularly shaped samples were required for physical tests, particularly hardness testing.

3.2.4 Compositional Analysis

Two methods identified in the literature review as being suitable for rubber compositional analysis were trialled to determine the extent of compositional variation between different tyre sections. The two methods used were Fourier Transfer Infrared Spectroscopy and Thermogravimetric Analysis.

FTIR was trialled first as it was a rapid and more basic test to determine the types of rubber used in different tyre sections. Rubber samples were subjected to a range of infrared light wavelengths and recorded transmission against energy light wavenumber (inverse wavelength) as shown in Figure 2.8. Rubber hydrocarbon types present in the sample were identified by the wavelength of characteristic peaks in the intensity-wavenumber spectrum. Solid rubber was not suitable for testing as it did not allow sufficient transmission of the infrared light through the sample to be measured. A small section of each rubber sample was pyrolysed in a test tube to produce liquid and when placed between two salt plates a thin film formed which was provided sufficient transmission of light for testing.

Repeat testing of the same sample resulted in different spectrums being produced, with shifts in the peaks used to identify the types of rubber used. These differences were attributed to the method used to heat rubber samples which was not a highly controlled process conducted in an unprotected atmosphere. Further testing was not conducted as it was not considered to be accurate enough to confidently identify the types of rubber hydrocarbons present in the compounds.

Thermogravimetric Analysis (TGA) offered a second method of determining the composition of recycled rubber particulate with the advantage of allowing solid sections of rubber to be analysed. The method required determining the mass loss of a sample while it was heated at a constant rate of 10°C/min in nitrogen and air. An example of the resulting mass loss-temperature graph and its derivative DTGA graph is given in Figure 3.3. Steps in the mass loss-temperature graph indicate different components of the rubber compound being pyrolysed.

TGA provided the proportion of volatiles (oils and extenders), base rubber hydrocarbons, organic filler (carbon black) and ash (inorganic fillers, residual catalyst) for each rubber compound. The DTGA curve, produced by calculating the derivative of the TGA curve, displays peaks during rubber hydrocarbon pyrolysis that occur at temperatures characteristic of the rubber hydrocarbons present.

Repeat testing of the same sample by TGA showed good repeatability of the method, with volatiles, rubber hydrocarbon, organic filler and ash contents all falling within 2% of the average measurements for three separate tests. The ability to use solid sections of rubber avoided the problems of sample preparation repeatability that occurred for FTIR tests and also provided greater compositional detail by quantifying filler, oil, rubber hydrocarbon and ash content.

3.2.5 Physical Properties

A range of standard physical property tests for rubber have well-established testing procedures. Many of these tests, such as glass transition temperature and electrical properties, are not relevant to rubber used for shockpad construction. Tests relevant to recycled rubber particulate such as density and hardness were restricted by the small size of the particulate at the end of the granulating process. Samples of each major tyre section (Section 3.2.3) were used in place of rubber particulate to determine a range of physical properties for the supplied recycled rubber particulate. The standard procedures used to conduct density and hardness measurements are detailed in the following sections.

3.2.5.1 Density measurements

The density of each tyre section sample was measured according to BS 903-A1:1996 Physical Testing of Rubber – Determination of Density - Method A. A mass balance was used to measure the mass of the rubber in air and suspended in distilled water at 23 °C. A metal sinker with a mass of 2 grams was attached to the rubber samples with a thin nylon wire to ensure adequate submersion of the rubber sections in water. Density for each rubber sample was determined using Equation 3.6. Three tests were conducted on each sample to provide an average density.

$$\rho = \frac{m_{ra}}{m_{ra} + m_{sw} - m_{srw}} \qquad \text{--------- Equation 3.6}$$

Where:

ρ	=	Rubber Density [grams.cm^{-3}]
m_{ra}	=	Mass of rubber in water [grams]
m_{sw}	=	Mass of sinker in water [grams]
m_{srw}	=	Mass of rubber and sinker in water [grams]

3.2.5.2 Hardness measurements

Hardness measurements on tyre section samples were conducted according to BS 903-A26:1995 Physical Testing of Rubber – Method for Determination of Hardness – Method N. The standard procedure used an indenting device to measure the difference in indenter depth for small and large applied forces. Results were converted to International Rubber Hardness Degrees (IRHD) using a standard table.

One measurement was conducted at three locations on each test sample to provide an average hardness. Inner liner and sidewall samples were thinner than the minimum standard thickness and therefore results would be influenced by the rigid surface below. Additional layers of the corresponding sample were used below to increase thickness to 10 mm to correspond with the standard thickness.

3.2.6 Mechanical Properties

The literature review revealed no standard tests to measure the mechanical properties of rubber particulate. Samples from tyre sections used for the physical and compositional tests were not large enough to conduct standard mechanical tests for rubber materials such as tensile strength, compressive modulus and rebound resilience. The rubber particulate produced at the end of the granulating process was too small to conduct these standard rubber tests.

A number of different options for mechanical tests were considered. Ideally, the test would be performed at high strain rates to simulate the frequency of loading applied during player and ball interactions. However, the impact tests were not suitable due to difficultly in removing air voids, dislodgement of the rubber particulate during the tests and limitations of the tensometer which was capable of removing air void but could not simulate appropriate loading rates. The construction of solid blocks of rubber from particulate was also considered, however the effects of the compression and heat required may have unduly altered the mechanical properties of the particulate.

Two different tests to determine the mechanical properties of rubber particulate were devised for comparison; gyratory compaction and vertical compression. Both tests used 'quasi-static' strain rates, but overcame the drawbacks of impact testing. They aimed to measure a mechanical property which was able to characterise recycled rubber particulate and also be sensitive enough to detect changes between different batches. A randomly selected batch of recycled rubber particulate was used to provide a benchmark, by which other samples could be compared. The development process and test procedure for the gyratory compaction and vertical compression tests are outlined in the following sections.

3.2.6.1 Gyratory Compaction

The Superpave gyratory compaction device was developed to simulate the in-service compaction process of asphalt road constructions (Harman et al, 2001). The device measures the workability of the test material by applying a set number of gyrations under a constant stress at an angle to reduce the void proportion within the test material. The resulting graph which displays void ratio against number of gyrations is shown in Figure 3.4.

It was hypothesised the gyratory compaction test may provide a useful method to measure the workability of recycled rubber particulate. The workability of rubber particulate is a measure of how easily the rubber can move or deform to fill the void space when placed under a load and is therefore dependent on rubber shape, size range, size distribution and also the mechanical properties of the rubber. Rubber shape, size range and size distribution influence the friction and interlocking between particles and their ability to permanently move to fill void space. The mechanical properties of the rubber influence the ability of the rubber to temporarily deform to fill void space. Measurements of workability conducted under loads high enough to produce elastic deformation of the rubber may therefore be a useful test to indicate changes in the mechanical properties of rubber particulate.

A test programme to trial the gyratory compaction test as a suitable mechanical test to measure and detect changes in the mechanical properties of recycled rubber particulate was developed. Rather than testing recycled rubber particulate from two different sources, the workability of one source of recycled rubber particulate was compared with recycled Ethylene-Propyl-Diene Monomer (EPDM) rubber. The EPDM was manually easier to deform and had a more cubic shape than the recycled rubber particulate and would therefore demonstrate the sensitivity of the test to significant changes in composition, mechanical and physical properties and processing method.

EPDM rubber was supplied in a 1 to 3 mm size range so recycled rubber particulate was combined in a size range of 1 to 3.35 mm to closely match the EPDM rubber size range as possible. The standard test for gyratory compaction of asphalt materials was used which involved samples of each rubber type being placed in a mould of 150 mm diameter. A constant 600 kPa stress was applied at an angle of 1.25 degrees to the vertical. Gyrations were applied at a rate of 30 gyrations/min up to a maximum of 500 gyrations to achieve a plateau in void ratio. Initial tests showed the standard 600 kPa stress produced sufficient movement of rubber particulate to rapidly produce the plateau in void ratio which is associated with deformation of the rubber particles themselves.

3.2.6.2 Vertical Compression Test

An alternative test method for measuring the mechanical properties of recycled rubber particulate was also developed as gyratory compaction equipment is a specialised machine that is not typically owned by sports pitch testing companies and would therefore be more difficult to implement as a standard test. The alternative test method measured the force-deflection behaviour of rubber particulate subjected to repeated vertical compressive loads. The vertical compression test used equipment readily available in all sports surface test companies.

The vertical compression test was in principle similar to the gyratory compaction test. A maximum load was applied to a sample of rubber particulate, placed in a mould, over a number of cycles to produce elastic deformation of the rubber particulate. Overall deformation of the sample batch was produced by a combination of permanent deformation produced by the rubber overcoming friction and interlocking to fill voids and elastic deformation of the rubber as with gyratory compaction, and again the load was required to be large enough to produce elastic deformation of the rubber to observe mechanical property changes. However, the vertical compression test provided information regarding behaviour of the rubber particulate during loading and unloading that the gyratory compaction test was not able to provide.

A programme was devised to develop a suitable test for characterising mechanical properties rubber particulate used to construct shockpads for this research project and provide a benchmark for measuring mechanical property changes for other sources of rubber particulate. Recycled rubber particulate and EPDM rubber were tested to determine the sensitivity of the test in describing mechanical property changes. The EPDM rubber was supplied in a 1 to 3 mm size class and the recycled rubber particulate of 1 to 3.35 mm size class was sieved from a 25 kg batch according to Section 4.2.3 (Chapter 4). The rubber particulate was contained within a rigid mould of 153 mm diameter specified in BS 5835 for compaction tests on soils which are 20 mm in size or smaller. The mould had rigid walls to prevent warping during loading and holes in the base to release air during compression.

A 1.75 kg mass of rubber particulate was placed loosely into the mould. The depth of the sample from the top of the mould was measured to provide a reference point for deflection. Preliminary tests showed the method was sensitive to the initial compaction applied to the rubber. A standard pre-compaction load of 0.5 kN was applied by the machine through a 149 mm rigid steel bearing plate to provide a controlled initial compression force on the rubber.

When filled, rubber in the mould was configured in a structure similar to a shockpad with a large portion of air voids. Applying one load cycle to the rubber particulate would only measure the force-deflection behaviour of the structure which would also be influenced by air voids and their configuration and not of the rubber itself. A number of load cycles of sufficient magnitude were required to be performed for the rubber to overcome internal friction and interlocking and fill air voids to produce a structure similar to a solid section of rubber. Once void spaces were sufficiently filled, the effect of voids on the measured behaviour was reduced and the overall behaviour became more influenced by the rubber itself.

A 5 kN load (equivalent to a stress of 270 kPa) was deemed sufficient from preliminary testing to permanently reduce the void space within the mould and ensure the mechanical properties of the rubber were being examined. Five consecutive compression cycles were applied to each rubber particulate sample at a rate of 25 mm deflection/min up to the load limit of 5 kN, and the deflection of rubber fill recorded for each cycle. Results were recorded as percent deflection against load for each cycle, an example is shown in Figure 3.5. Preliminary testing showed the deflection of the rubber to reduce with each cycle due to permanent movement of the rubber particles. After 4 cycles the change in deflection due to rubber movement was deemed minimal, therefore the fifth cycle was used to measure the mechanical properties of the rubber particulate.

3.3 Composition and Properties of Recycled Rubber Particulate

The following sections provide the results of characterisation testing on the supplied batch of recycled rubber particulate. Calculations of mass proportion for major tyre sections within the batch of particulate and composition and physical properties conducted on samples of each major tyre section are provided together with preliminary results for the two test methods developed to measure the mechanical properties of rubber particulate.

3.3.1 Mass Proportion of Tyre Sections

The mass proportions of each major tyre section expected to be contained within the supplied batch of recycled rubber particulate were determined from tyre section dimensional measurements as a proportion of the tyre mass. The mass proportions of the tread, sidewall, apex and inner liner sections and 'other rubber' contained in each tyre size measured are given in Table 3.1, together with an average proportion for the a batch of particulate assuming a 1:1 ration of the two tyres contained in the feedstock.

The measurements were similar for the two tyres, however the 385/65 R22.5 was wider than the 295/80 R22.5 tyre. The increased width of the tread increased the proportion of tread rubber obtained from the tyre, however most other sections, particularly sidewall and inner liner, showed a similar content of rubber was obtained from each section for the tyres. The tread section constitutes approximately half of the rubber particulate (48%). The sidewall constitutes the second highest proportion of the particulate at 18% and the inner liner, apex and 'other rubber' constituting smaller proportions.

The 'other rubber' section grouped together rubber components of the tyre such gum chafer, wire skim and shoulder which were identified in the literature review as being negligible in terms of proportion to other major tyre sections. Wire skim is used in tyres to increase the bond between steel wire and other rubber sections of a tyre and is therefore well bonded to the wire. When the steel is removed from the tyres in the granulation process, some wire skim rubber remains on the wire and is therefore not present in the final rubber particulate produced. The actual quantity of rubber retained on the wire is not known or able be easily estimated; however, the proportion of 'other rubber' contained in the batch of typical recycled rubber particulate would be likely to be less than the 7% that was calculated, leading to other major tyres sections accounting for a greater proportion.

The steel content of tyres was assumed to be 30% of its mass, which was based on the sources of literature available. Reducing the steel content of tyres from 30 to 20% significantly affects the 'other rubber' content of the tyres from 7 to 21%. The steel content may vary widely between different manufacturers and tyre sizes, however, due to tyre manufacturers not publishing construction details of their products such detailed information was not available to produce statistical data to enhance the accuracy of the calculations carried out in this study.

3.3.2 Composition

Thermogravimetric Analysis (TGA) was conducted to determine the variation in composition of major tyre sections with respect to their proportion of the supplied batch of recycled rubber particulate. A typical graph obtained from TGA is given in Figure 3.3. The steps in the graph identify the pyrolysis of each component of the rubber compound as it is heated. Results of the analysis, given in Table 3.2, show the average proportions of the volatiles, rubber hydrocarbons, fillers and ash components for each major tyre section. Temperature peaks of the DTGA curve were also used to identify the different rubbers used for each section; this is also given in Table 3.2.

Measurements for volatiles represent extender oils and plasticisers used in the rubber compound to increase ease of manufacture and reduce expensive rubber hydrocarbon content. Tread sections contained the highest volatiles content of all major tyre sections with 14%, but also the largest standard deviation. Both high volatiles content and variation can be explained by the feedstock containing tyres with original treads and retreads. Re-treaded sections are extruded and therefore use plasticisers. An increased proportion of SBR rubber is also often used in re-treaded sections which may include extender oils also to reduce costs. A feedstock containing a mix of re-treaded and original tyres would account for the increased standard deviation.

Fillers, such as carbon black, are added to rubber compounds to increase resistance to wear, increase stiffness and reduce rubber hydrocarbon costs. The high filler content of the apex section is reflected in its high hardness and also its function to stiffen the lower sidewall section of a tyre. Tread and sidewall sections show similar filler contents at approximately 35%, with the inner liner having a relatively low filler content of 20%. Filler content shows standard deviations ranging from 4.8 to 7.7 for tread, sidewall and apex sections, which is considered significant when compared to the standard deviation of 1.7 for the inner liner.

The ash remaining at the end of TGA contained inorganic components of rubber particulate that could not be pyrolysed such as catalyst residues and inorganic fillers. Ash contents were similar for tread, sidewall and inner liner sections; however the apex section contained a raised residual ash content of 10%. The high ash content is most likely due to fillers in addition to carbon black to stiffen the section.

The rubber hydrocarbon content constituted the majority of the rubber compound mass with the exception of apex where it was approximately in equal proportion to filler content. The inner liner content was significantly higher at 71% compared to tread, sidewall and apex sections which ranged from 41 to 55%. Tread and sidewall sections were shown to contain a mix of natural rubber and styrene-butadiene (or butadiene rubber), while apex sections were contained only natural rubber. The rubber used to construct inner liners could not be identified.

Compositional variation was observed between all major tyre sections and also within measurements for the same section. Differences within measurements of the same section are attributed to the range of compound compositions used by tyre manufacturers, and those for the tread sections can be further explained by the original and re-treaded mix. The tread and sidewall sections show the most similarity in terms of the rubber hydrocarbon and filler contents, which constitute the majority components of the rubber compound, and inner liner and apex sections vary either side of this middle composition. Tread and sidewall sections constitute 73% of the typical rubber particulate batch, with the apex and inner liner constituting smaller proportions in comparison.

3.3.3 Physical Properties

Physical property variation within the batch of rubber particulate was not considered to be significant. Tread, sidewall and inner liner sections were almost identical for density measurements given in Table 3.3, ranging from 1.12 to 1.13 g/cm^3. The apex section was slightly raised at 1.16 g/cm^3, however, standard deviations show apex density lies within one standard deviation of the other tyre sections

Hardness measurements, given in Table 3.3, show comparatively high hardness exhibited by tread and apex sections. This result is expected for tread sections to provide reduced wear rates through contact of the tyre with the road. A well established proportionality between hardness and modulus of materials indicates the high hardness of the apex would be due to its function of stiffening the tyre sidewall adjacent where the tyre and rim come into contact as shown in Figure 2.7. The comparatively reduced hardness of the sidewall and inner liner are reflected in their low wear and low stiffness requirements in a tyre. The same variation in standard deviations between samples of the same tyre section is reflected in hardness and density measurements. These variations are accounted for by different formulations used by tyre manufacturers and also possible age differences between tyres. Tread sections are particularly subject to variation as a mix of original and re-treaded tyres may be present in the feedstock which exhibit property variations due to different formulations.

Average values for density and hardness measurements weighted against the section proportion in the batch of rubber show negligible variation in density for the batch of recycled rubber particulate. Some variation from the average is exhibited for hardness measurements. However, the hardness measurements of tread, sidewall and apex sections lay approximately one standard deviation from the average, accounting for 83% of the hardness of the batch of rubber. In comparison, the small proportion of softer inner liner does not significantly contribute to hardness variations in the batch of recycled rubber particulate.

3.3.4 Mechanical Properties

In the absence of appropriate mechanical test equipment to measure the mechanical properties of small samples of each tyre section, preliminary investigations into two tests were conducted to assess their ability to measure the mechanical properties of a small portion of recycled rubber particulate. These two tests were gyratory compaction, which was adapted for rubber particulate from its intended use to measure the workability of asphalt materials, and a vertical compression test. The sensitivity of the test was measured by comparing mechanical property results for recycled rubber particulate with EPDM rubber to determine the extent of mechanical property change for a different rubber type.

Preliminary measurements for recycled rubber particulate and EPDM rubber using the gyratory compaction test are shown in Figure 3.4. The void proportion is shown to rapidly decrease during the first gyration and begins to plateau after 15 gyrations. In the first 15 gyrations the void proportion reduced from 15.8% to 12.7%, and over the full 500 gyrations of testing, void proportion reduced further to 11.5%. The EPDM rubber shows a different workability to the recycled rubber particulate. Void ratio initially drops rapidly from 19% to 12% over 20 gyrations, but does not demonstrate the same sharpness to the curve as the recycled rubber particulate and continues to reduce in void proportion to 10% over 100 gyrations. Overall, the void proportion of the recycled rubber particulate was reduced by 4.3% and the EPDM rubber by 9%. This difference may be due to the initial compaction of the rubber when it as placed in the mould and may therefore require some initial compression or vibration to ensure the same initial compaction prior to testing.

Vertical compression tests were conducted on 1 to 3.35 mm recycled rubber particulate, 1 to 3 mm EPDM rubber and 3.35 to 5 mm recycled rubber particulate to characterise recycled rubber particulate and measure the sensitivity of the test to changes in rubber composition and rubber size. The force-deflection behaviour of the 1 to 3.35 mm recycled rubber particulate over five compression cycles is shown in Figure 3.5. Deflection was zeroed at the beginning of each cycle; therefore the deflection produced during each cycle is shown by the respective curve.

The first cycle produced a 55 mm maximum deflection of the rubber, which was reduced to 20 mm by the fifth cycle. The change in maximum deflection between the first and second cycles was 32 mm which is considered significant. A 3 mm change in maximum deflection occurred over the final four cycles, which showed the first cycle had displaced the majority of rubber particles into available air voids. The final four cycles began reaching a plateau near the fifth cycle, which provided a more accurate measurement of the compressional behaviour of the rubber with minimal influence from air voids. The force-deflection behaviour of the rubber particulate provided the measurement of two mechanical properties; average stiffness and peak deflection. The fifth cycle provided a peak deflection of 20 mm and an average linear stiffness of 250 kN/m.

A comparison of recycled rubber particulate and EPDM rubber behaviour using the fifth cycle of the vertical compression test is provided in Figure 3.6. The mechanical properties of the EPDM rubber were measured at 16 mm peak deflection and 250 kN/m for average linear stiffness. The 20% difference in both peak deflection and stiffness between the two different rubber types is considered significant in terms of test sensitivity for measuring changes in the mechanical properties of rubber particulate. Increasing rubber size to the 3.35 to 5 mm size range provided a 1 mm decrease in peak deflection and 13 kN/m increase in average linear stiffness. This 5% difference for both mechanical properties is not considered significant at this stage of method development; however, repeat tests would assist in determining standard errors and determine the effect of rubber size.

3.4 Discussion

A detailed study to characterise the composition and subsequent physical and mechanical properties, rubber shape and size range and size distribution of recycled rubber particulate produced by various suppliers for shockpad constructions would constitute a project within itself and was therefore not within the scope of this research project. The selection of recycled rubber particulate from one supplier to construct all shockpads for this research project controlled rubber shape, allowed rubber size range and size distribution to be varied and allowed preliminary characterisation of recycled rubber particulate in terms of composition and physical and mechanical properties. The composition and physical properties of various sections of truck tyres were compared to their calculated proportion in the supplied particulate and in addition to mechanical property measurement, the potential for the particulate to produce variation in shockpad mechanical properties and behaviour was assessed. A discussion of these results and the implications of rubber composition variability on the overall properties and behaviour of shockpads are provided in the following section.

The preliminary study to calculate the mass proportion of tread, sidewall, apex, inner liner and 'other rubber' in the supplied batch of rubber particulate from tyre feedstock dimensional measurements showed tread and sidewall sections constituted the main proportion of the particulate, with apex and inner liner and 'other rubber' constituting smaller proportions. The mass of tread, sidewall, apex and inner liner sections were calculated from tyre measurements and the 'other rubber' proportion calculated from the remaining rubber mass of the tyre once the steel mass had been subtracted. The proportion of 'other rubber' was shown to be significantly affected by the assumed steel content, however the proportion of steel contained in truck tyres was not able to be accurately established from the literature review or calculated from tyre dimensional measurements. Further estimations of measurements for sidewall thickness and apex area may have affected the relative proportions of each section calculated. However, the method provided a good initial assessment of the relative proportions of each tyre section contained in a typical batch of recycled rubber particulate. A wider study examining feedstock and waste products of the granulation process would provide a more accurate assessment.

Thermogravimetric Analysis was used to quantify proportions of rubber hydrocarbon, volatiles, carbon black and inorganic fillers in the major sections of truck tyres. Tread and sidewall sections showed similarity in rubber hydrocarbon to filler ratio and ash content. The composition of the apex and inner liner sections varied either side of this average with the inner liner having a very high rubber hydrocarbon to filler ratio and apex having a comparatively low rubber hydrocarbon ratio. Combined, the tread and sidewall sections constitute 73% of the rubber mass contained within a tyre. Hence, the smaller proportion of inner liner and apex sections are not thought to produce significant variations within the composition of the supplied batch of recycled rubber particulate.

A comparison of TGA results with those of other researchers for various types of rubber particulate (summarised in Table 2.7) show mixed agreement. Proportions of each component for the tread section agree well with those measured for particulate derived from tread sections by Rouse (1997), with all components falling within one standard deviation of the measured values. However, measurements for the inner liner section do not compare so well to those of Manual and Dierkes (1997), as lower volatile and filler contents were measured and there was a 17% increase in rubber hydrocarbon content. The lack of any published data for whole truck tyre particulate prevents any conclusive statement regarding magnitude of compositional variation between different rubber particulate producers from being reached.

The compositional variations between different tyre sections for this batch of rubber were not anticipated to produce considerable differences in the physical and mechanical properties of the rubber particulate due to the similarity between tread and sidewall sections which constituted approximately three quarters of the batch of recycled rubber particulate. Links between composition and physical properties are exhibited by the inner liner and apex sections of the tyre. The inner liner had a distinctly higher rubber hydrocarbon to filler proportions compared to other tyre sections resulting in a lower hardness value. Conversely, the high filler content of the apex resulted in a high hardness value and higher density compared to other tyre sections. Apex and inner liner sections were shown to produce small deviations in the physical properties of the rubber particulate. Overall, the physical properties for the batch of rubber particulate, represented by the weighted averages for density and hardness measurements, were not shown to be significantly influenced by any major tyre section, as the apex and inner liner sections constitute such a small proportion.

The samples of tyre sections used for compositional and physical property tests were not suitable for mechanical property testing due to their size and non-availability of suitable test equipment; therefore, the difference in mechanical properties for each tyre section could not be assessed. Alternatively, two test methods that examined the mechanical properties for small batches of rubber particulate were developed; gyratory compaction and vertical compression.

Preliminary measurements of mechanical properties showed both methods were sensitive enough to measure changes in rubber composition. However, results from the two different test methods are difficult to compare as the gyratory compaction test applies a constant stress over twice that of the maximum stress applied by the vertical compression test. The difference between the constant stress applied by the gyratory compactor and the variable stress applied by the vertical compaction test leads to two different methods of presenting mechanical property results.

The primary use of the gyratory compaction test to predict the densification of road materials while in-service means it was developed for testing stone aggregate and bitumen mixtures. The rubber possesses more elasticity than the stone aggregate and therefore did not reach a plateau in void proportion as required to obtain maximum densification which is the mechanical property provided by gyratory compaction test results. However, the application of a constant stress does not simulate cyclic loading applied to the rubber particulate in-service and an estimate of maximum densification, which can be obtained from test results, only serves to provide an index to rank different rubber types to determine an effect from rubber type. In addition, the gyratory compactor is a specialised compaction device that is not owned by sports pitch testing companies who are likely to be performing mechanical property testing of recycled rubber particulate for characterisation purposes.

The vertical compression test used a tensile testing machine to apply compressional loads to the rubber particulate. Unlike gyratory compactors, tensile testers are commonplace equipment for sports pitch testing companies who require the device to conduct tensile tests on shockpads and carpet samples. Initial measurements using the vertical compression test show potential for the test to detect changes in the mechanical properties for different sources of recycled rubber particulate. The test was able to measure the force-deflection behaviour during each compression cycle and after sufficient reduction of the air voids, displayed mechanical properties of the rubber through measurements of maximum deflection and average linear stiffness during the fifth compression cycle. Maximum deflection and average linear stiffness are material properties that can be compared for different sources of recycled rubber particulate. Through further development of the test to estimate standard errors, acceptable values for each mechanical property could be determined to provide a quality control test for the characterisation of the compressibility of recycled rubber particulate.

These results of compositional and physical property tests did not indicate any significant variations in the batch of recycled rubber particulate that may influence the overall mechanical properties and behaviour of the shockpads the batch of recycled rubber particulate is used to produce. In addition, although the rubber particulate constitutes approximately 90% of the shockpad by mass, it only constitutes approximately 50% of the shockpad by volume when the air voids are considered. During development of the vertical compression test, air voids were shown to affect the force-deflection behaviour during the first compression cycles producing a non-linear curve similar to that of a shockpad as measured by Walker (1996). The effect of the air voids will diminish the effect of any rubber variability on shockpad mechanical properties for small strains, however, for larger strains which reduce air voids, the mechanical properties of the rubber and any variability is expected to be influential. These results provide assurance that the supplied batch of recycled rubber will not unduly affect the mechanical properties of the shockpads constructed in Chapter 4 of this thesis.

3.5 Summary

Recycled rubber particulate supplied to construct cast in-situ shockpads is currently only required to be classified in terms of particle size distribution and source material for its use. The construction of truck tyres from various rubber compounds was identified in the literature review. The lack of published investigations into the extent of this compositional variation and its potential effect on shockpad mechanical properties and behaviour required further characterisation of the rubber to be conducted to ensure shockpads constructed to examine the effects of mix design in Chapter 4 of this thesis were not unduly affected by the rubber.

Determination of major tyre section proportions for a typical batch of rubber and subsequent physical and compositional tests on each section showed some expected variation in hardness, density and rubber hydrocarbon to filler content for apex and inner liner sections. However, as the inner liner and apex sections constitute only a small mass proportion of the recycled rubber particulate when compared to the tread and sidewall sections; overall variability of the rubber supplied was not thought to influence the mechanical properties and behaviour of the cast in-situ shockpads it will be used to construct.

A comparison of two test methods devised to compare the mechanical properties of recycled rubber particulate showed vertical compression to be the preferred test. The vertical compression method supplied additional information in the form of force-deflection behaviour which was used to define both maximum deflection and average linear stiffness. Initial tests showed it to be a viable method for characterising the mechanical properties of rubber particulate.

Tyre Section	Mass Proportion of Rubber[%]		
	295/80 R22.5	385/65 R22.5	Batch
Tread	40.7	53.4	47.6
Sidewall	18.8	18.0	18.4
Inner Liner	8.9	8.2	8.5
Apex	10.0	8.6	9.2
Other Rubber	21.5	11.8	16.3

Table 3.1: Calculated proportion of each truck tyre section for individual tyres and supplied batch on a 1:1 ratio

Tyre Section	Volatiles [%]	Rubber [%]	Filler [%]	Ash [%]	NR	SBR/BR	Other Rubber
Tread	13.9 (2.4)	46.8 (4.8)	35.8 (7.7)	4.2 (1.7)	Y	Y	-
Sidewall	7.9 (1.2)	54.6 (3.3)	34.4 (5.1)	3.2 (1.7)	Y	Y	-
Inner Liner	5.7 (0.9)	70.8 (4.6)	20.5 (1.7)	3.0 (1.4)	-	-	Y
Apex	7.7 (1.3)	40.8 (8.4)	41.5 (4.8)	10.0 (1.7)	Y	-	-
W. Av	9.3	42.1	28.9	3.8			

Table 3.2: TGA and DTGA results showing the average composition of each tyre section from five tests. Standard deviations denoted in brackets

Tyre Section	Density [g/cm^3]	Hardness IRHD
Tread	1.12 (0.04)	63 (2.8)
Sidewall	1.13 (0.06)	57 (2.5)
Inner Liner	1.13 (0.06)	48 (1.7)
Apex	1.16 (0.01)	64 (3.8)
Weighted Average	1.13	60

Table 3.3: Average density measurements and IRHD hardness for major tyre sections from five tests.Standard deviations denoted in brackets

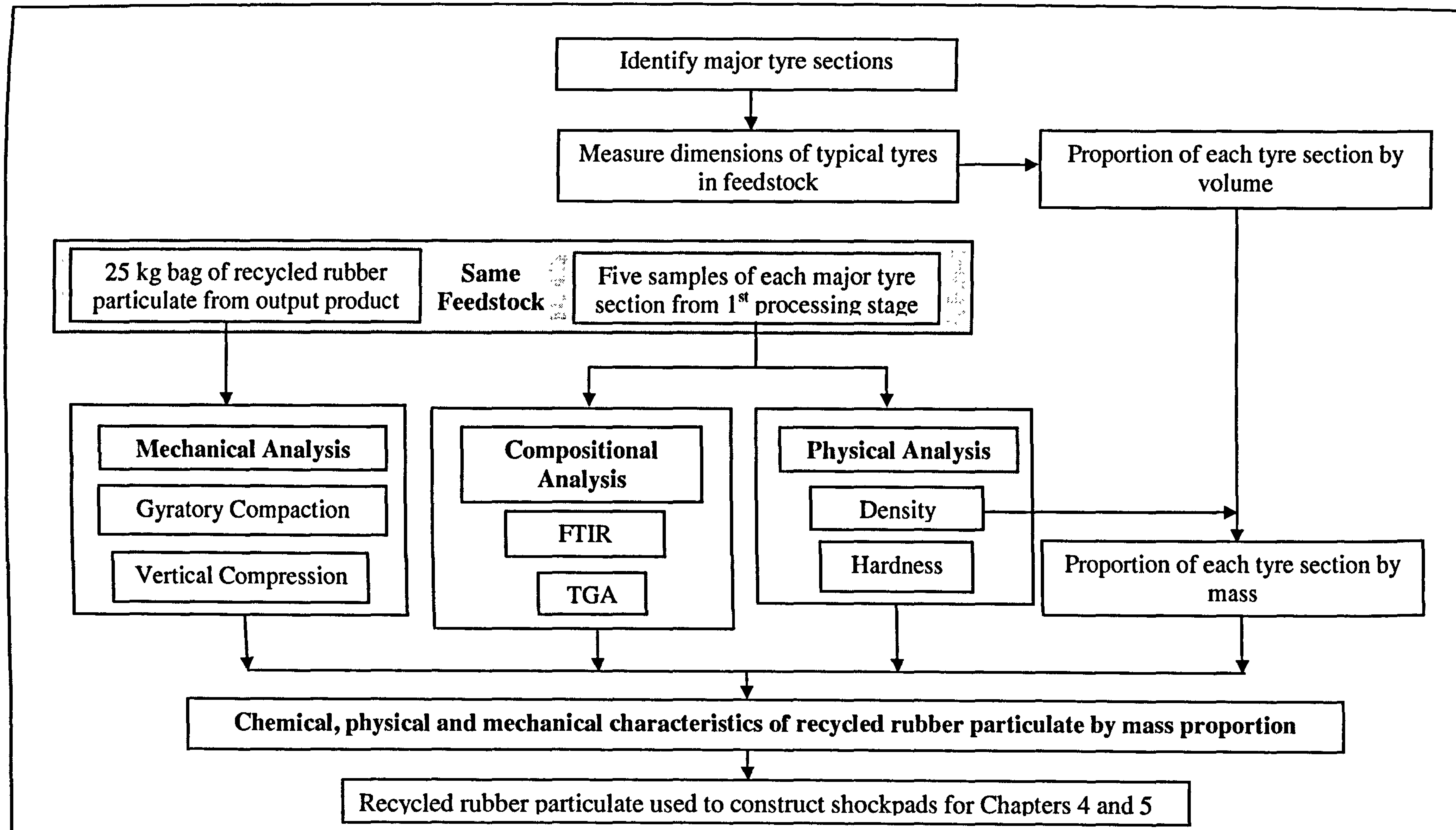


Figure 3.1: Flowchart of the process undertaken to characterise a typical batch of recycled rubber particulate.

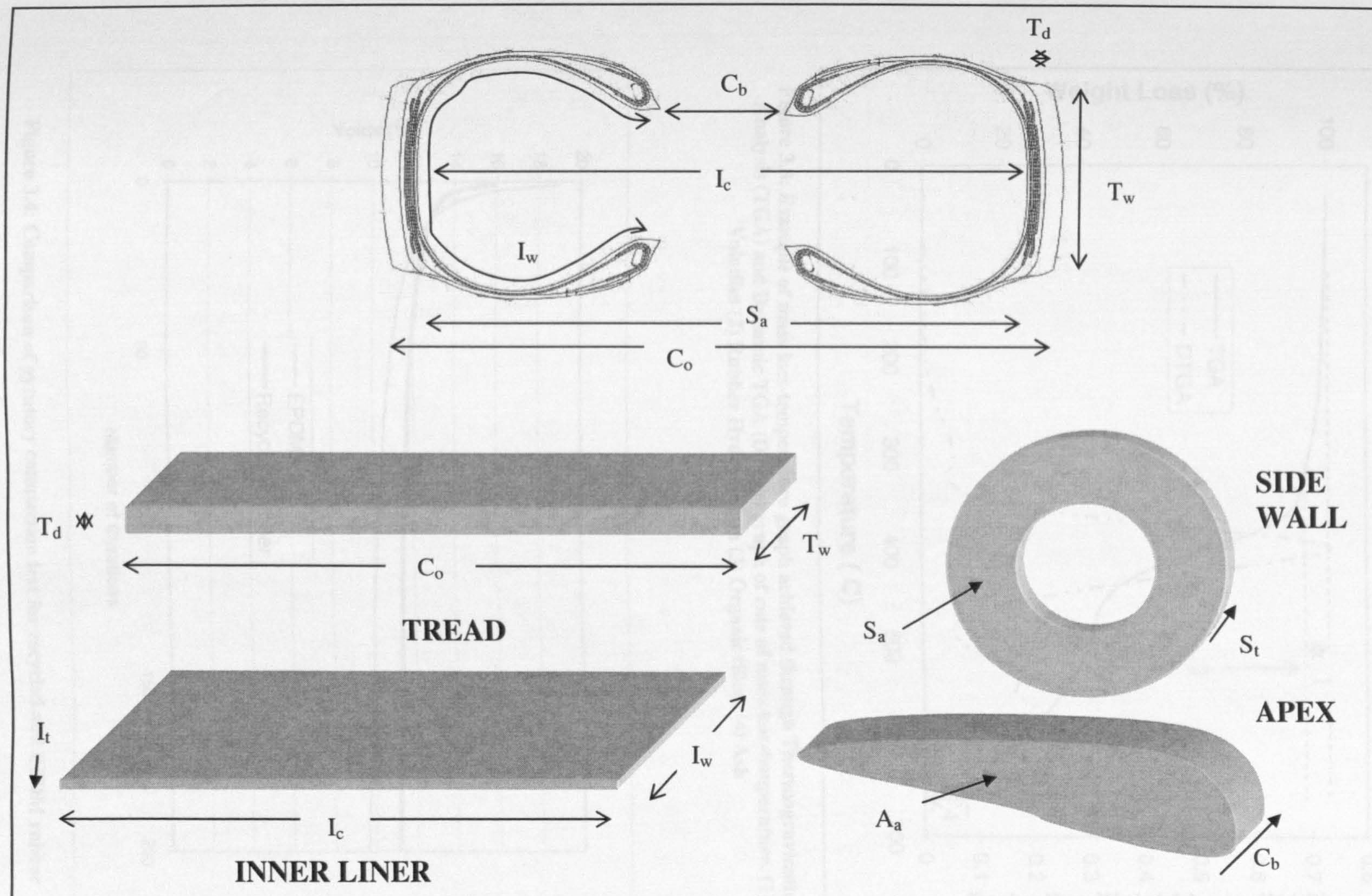


Figure 3.2: Dimensions of tyre sections

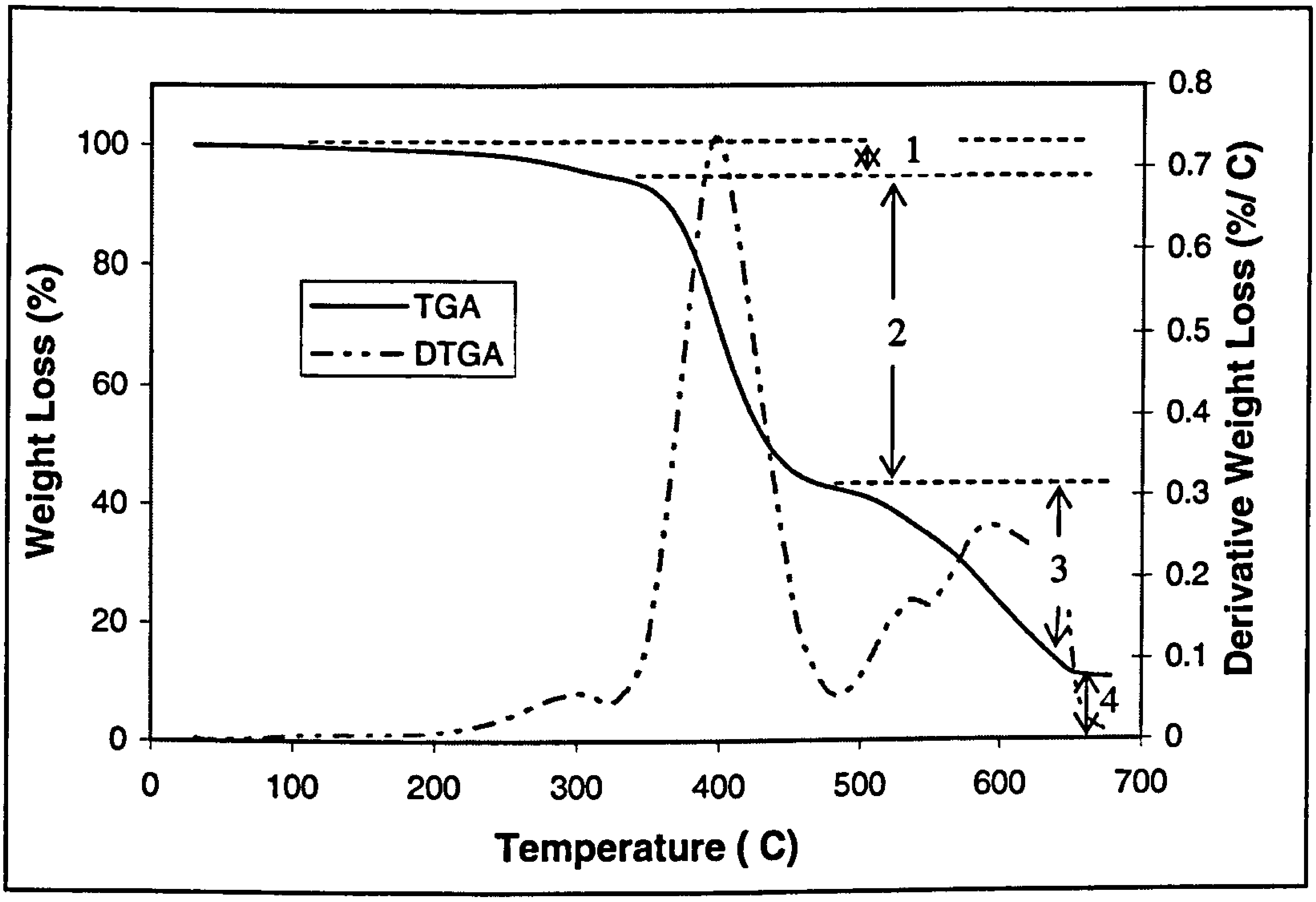


Figure 3.3: Example of mass loss-temperature graph achieved through Thermogravimetric Analysis (TGA) and Dynamic TGA (DTGA) graph of rate of mass loss-temperature. (1) Volatiles (2) Rubber Hydrocarbon (3) Organic fillers (4) Ash

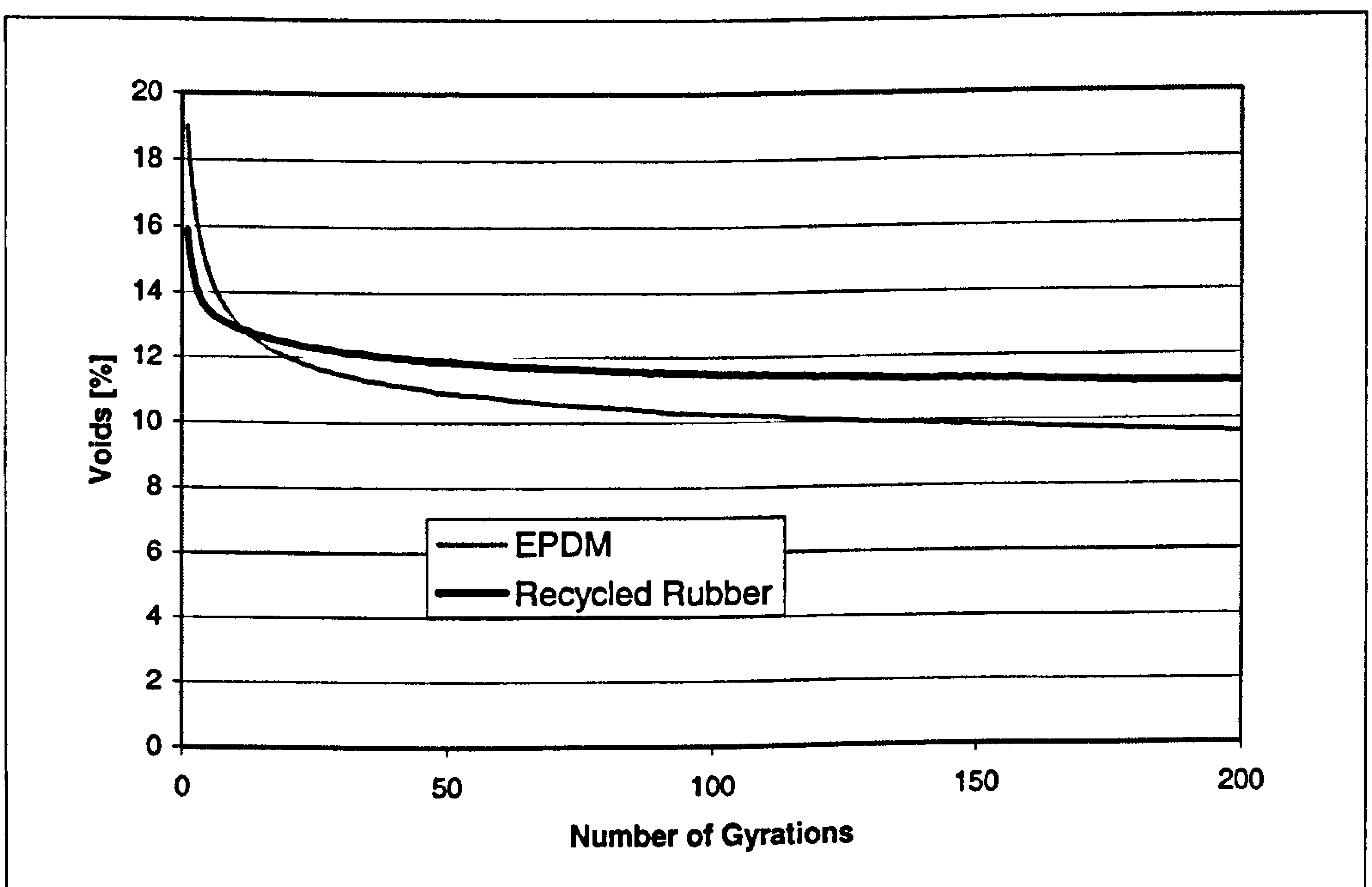


Figure 3.4: Comparison of gyratory compaction test for recycled and EPDM rubber

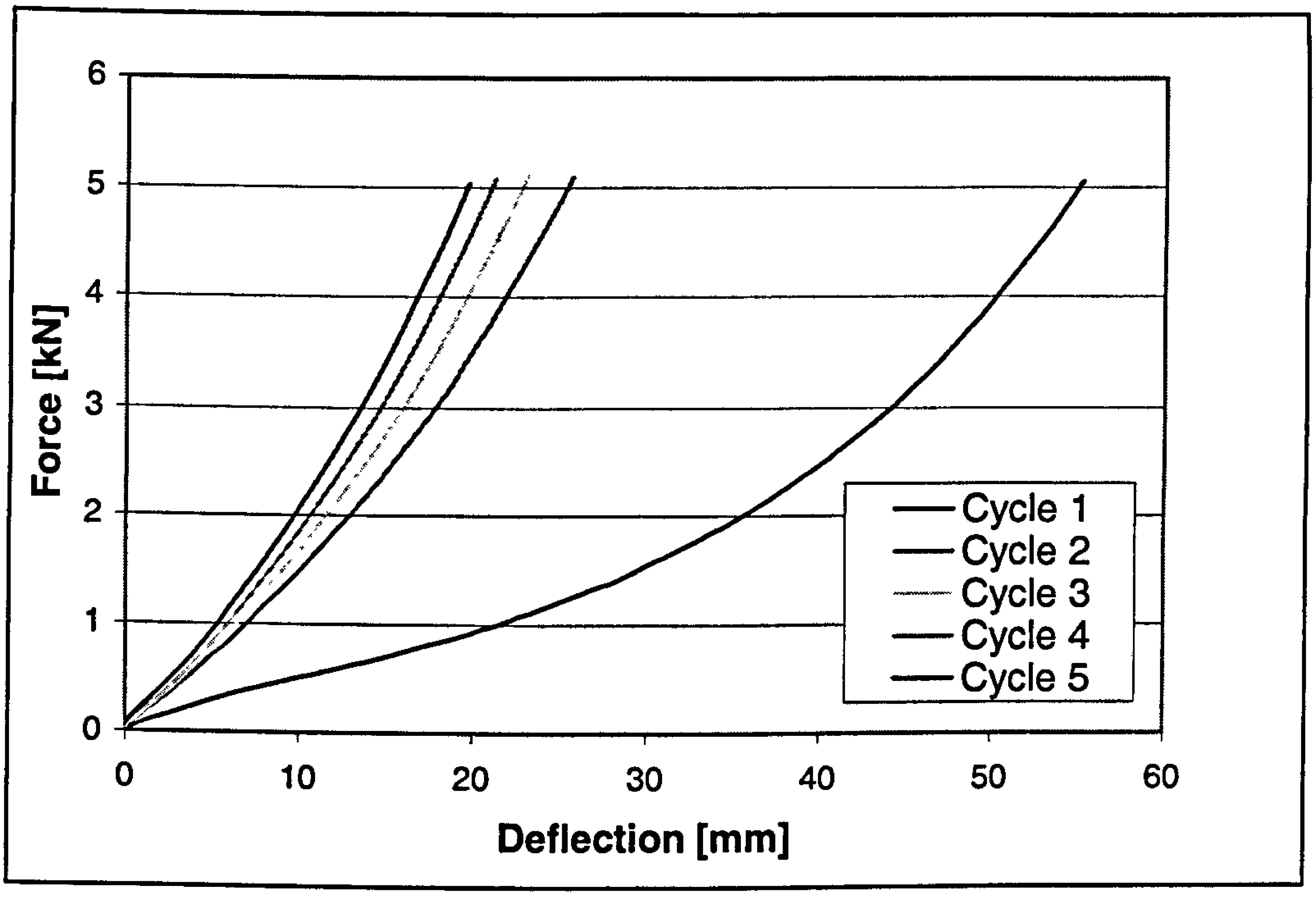


Figure 3.5: Changes in force-deflection behaviour over five compressions for 1 – 1.5 mm recycled rubber particulate

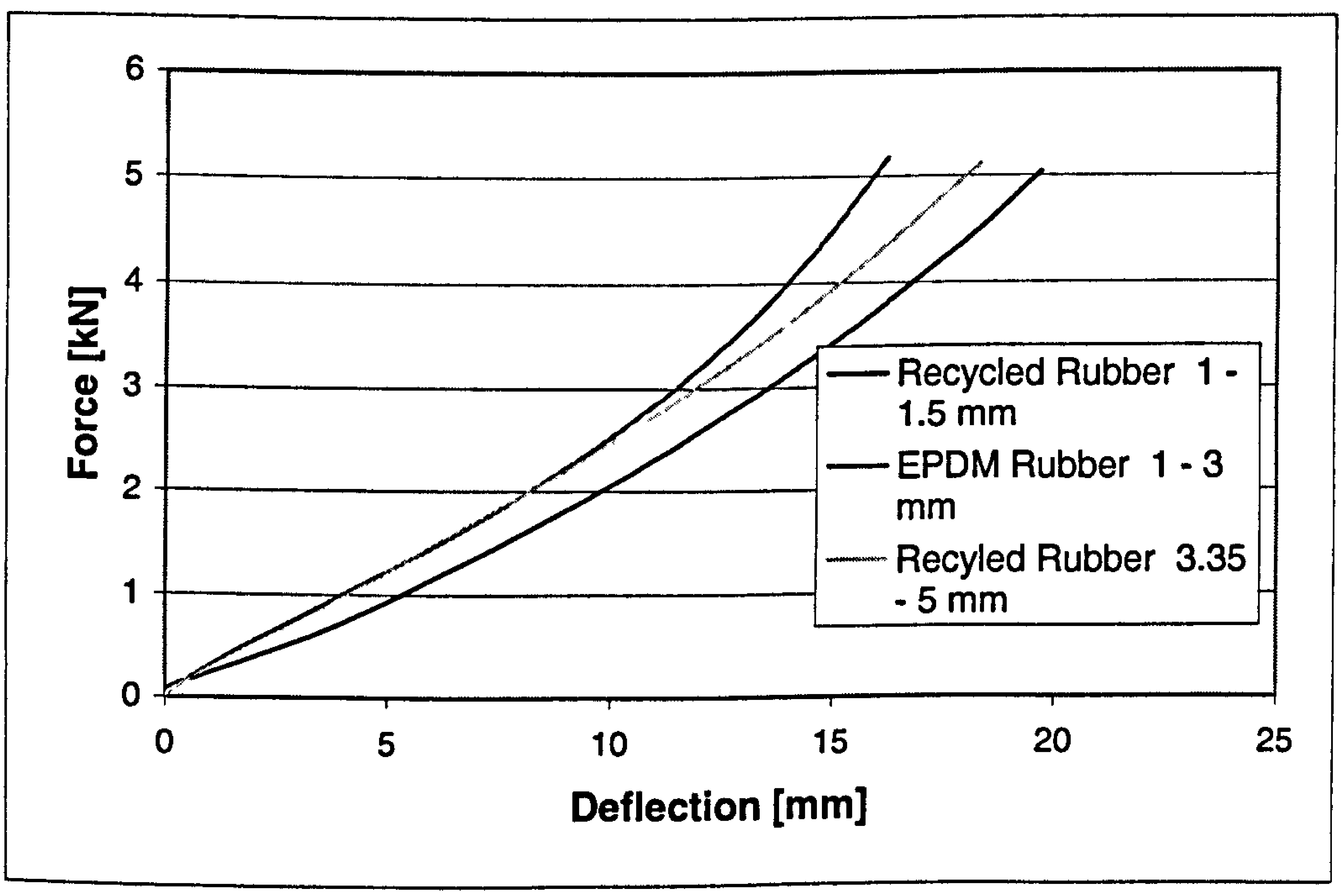


Figure 3.6: Vertical Compression Test comparing different rubber sizes and types

Chapter 4

MIX DESIGN AND MECHANICAL PROPERTIES

4.1 Introduction

The literature review (Chapter 2) identified the current industry practice for shockpad design, construction and testing. The lack of shockpad development was attributed to 'rule-of-thumb' measures and anecdotal evidence being used to by shockpad constructors to design and construct shockpad rather than through rigorous scientific investigation. Site visits to view the process undertaken in shockpad construction revealed many areas where possible variations from design specifications may occur. The review of verification methods and mechanical tests to ensure specifications had been met issued by sporting governing bodies was almost non-existent and therefore poor shockpad construction 'quality' would not be identified until after carpet installation or at a later stage when the pitch begins to degrade.

Tensile measurements are the most common test method used within the sports pitch construction industry to indicate the 'quality' of the shockpad produced. A minimum tensile strength requirement is used to indicate sufficient binder content of the shockpad and therefore sufficient durability. The use of tensile strength measurements to indicate durability was criticised in the literature review as there is little published evidence to support the link between tensile strength and durability. Tensile measurements are only concerned with the binder content of shockpads and not other mix design variables which may also affect the 'quality' or mechanical properties of shockpads.

Ten mix design variables were identified in the literature, however the effect of these variables on shockpad mechanical properties was not well identified in literature, with previous research into the effects of shockpad design on mechanical properties conducted by Kim et al (1997), Sobral et al (2003), Tipp and Watson (1982) and Young (2006). The shockpads constructed by Kim et al (1997), Sobral et al (2003) and Tipp and Watson (1982) contained rubber sizes and/or binder contents not representative of cast in-situ shockpads currently produced in the UK, and provided little detail regarding other design variables to allow their results to be reproduced or compared. Their use of the tensile test may indicate changes to pad durability; however, it did not provide information regarding changes to mechanical properties of ball and player interactions.

Young (2006) used a shockpad design representative of current cast in-situ shockpads constructed in the UK. Berlin Artificial Athlete, Clegg Hammer and Ball Rebound tests were conducted to determine how changes to shockpad thickness would affect performance aspects of the shockpad and the whole pitch construction. Significant changes in shockpad mechanical properties, due to thickness variations, were observed by Young (2006) and the mechanical test methods proved useful in measuring changes in mechanical properties. However, the effect of shockpad thickness on durability was not investigated and the shockpads used were detailed in terms of their mix design.

The work of Young (2006) provided a good basis for the development of a mechanical testing programme that could confirm the effect of thickness on shockpad and pitch performance and also investigate the effects of other design variables. The vertical ball rebound test provided a suitable ball interaction test and the Berlin Artificial Athlete and 2.25 kg Clegg Hammer suitable player interaction tests. The industry standard tensile test, and an additional cyclic fatigue test, were added to the test programme to evaluate shockpad durability indirectly.

In order to examine the effect of shockpad mix design variables on mechanical properties, a range of shockpads with variations in mix design were constructed. The rubber particulate supplied to construct the shockpads was characterised in Chapter 3 of this thesis, where it was concluded that variations in rubber composition and properties were not expected to produce variations in the shockpad it was used to produce. A test programme was developed which involved the design of a benchmark shockpad by which changes in mechanical properties could be measured.

Mix design variables of shockpad thickness, bulk density, rubber size and size distribution, binder type and binder content were examined as part of this investigation by constructing shockpads with a range of values either side of the benchmark shockpad. The method of constructing cast in-situ shockpad in moulds, described by Young (2006), was developed further to produce a repeatable laboratory construction method that was able to produce shockpads to precise mix design specifications.

The mechanical testing was conducted on shockpads and shockpad-carpet systems to determine the effect of mix design variables on shockpads and the whole pitch construction. Test results were used to identify key mix design variables that significantly affect shockpad mechanical properties and form the basis of recommendations for shockpad constructors and sporting governing bodies. Recommendations are made in identifying variables that require strict control during shockpad construction and specifications for testing to verify mix design specifications and mechanical property requirements have been met. Suitable alternative test methods for shockpads are also identified.

4.2 Experimental Methodology

4.2.1 Introduction

This section outlines the experimental methodology used to advance the current state of knowledge regarding shockpad mix design and its subsequent effects on the mechanical properties of shockpads and the whole pitch construction.

A flow chart outlining the process undertaken in test programme development and execution is provided in Figure 4.1. Ten mix design variables were identified in the literature review relating to constituent materials, design, construction and curing. An issue regarding the potential variability of the recycled rubber particulate was among those variables identified. Necessary measures were put in place to ensure each variable could be adequately controlled so as to not unduly influence the properties of the constructed shockpads while other variables were being examined. A decision was made to use one source of recycled rubber particulate to control the potential for variation in composition and mechanical and physical properties. The supplied rubber was characterised in Chapter 3 and determined to be a controlled variable in the shockpads it was used to construct.

Mix design variables of shockpad thickness, bulk density, rubber size and size distribution, binder content and binder type were able to be varied as part of this investigation. A benchmark shockpad was designed with the intention of reflecting the design of a 'typical' cast in-situ shockpad produced in the UK and a range for each of the identified mix design variables examined according to possible variations produced on-site. Industrial collaboration provided specifications for the benchmark shockpad and a range of suitable values for each variable. However, bulk density of shockpads was not able to be ascertained through this collaboration as manufacturers did not know the bulk density of the shockpads they produced and therefore required the characterisation of cured cast in-situ shockpads collected from site.

A method was developed based on that used by Young (2006) to construct small-scale cast in-situ shockpads in the laboratory. A number of trials were conducted to construct shockpads, however it was apparent from the literature review there were few published methods to verify the mix design of the shockpads. Alternative methods were developed during construction trials, such as weighing moulds before and after construction to determine binder content, which provided verification that a repeatable and accurate construction method had been developed.

Mechanical test methods to measure the effects of mix design were required for three functional aspects of shockpads; player interactions, ball interactions and durability, as these aspects control the suitability of the pitch. Publications of test methods by sporting governing bodies showed the Berlin Artificial Athlete to be a player interaction test for shockpads and tensile strength measurements to indicate durability. Criticism of these two mechanical tests was identified in the literature and therefore alternative test methods were also developed and evaluated. Young (2006) used the 2.25 kg Clegg Hammer as an alternative to the Berlin Artificial Athlete for player interaction tests on shockpads successfully and also adapted the industry standard vertical ball rebound test for the whole pitch construction for the shockpad layer in-situ. These two tests were used to determine player and ball interaction tests.

The absence of published specifications for a suitable alternative to the tensile test for the measurement of shockpad durability required one to be developed. This new durability test is referred to as the 'Cyclic Fatigue Test' throughout the remainder of this thesis.

The following sections detail the development of the shockpad design, construction, verification and mechanical testing for the investigation into the effects of mix design on shockpad mechanical properties.

4.2.2 Mix Design Variable Identification and Control

Ten mix design variables for cast in-situ shockpads were identified in the literature review and are listed in Table 4.1. These variables were identified as factors in shockpad constituent materials, design and construction that could alter mechanical properties and behaviour. This section examines the methods used to control and alter each of the identified variables.

Chapter 3 of this thesis characterised the batch of recycled rubber particulate that was supplied to construct cast in-situ shockpads. One source of rubber particulate was characterised as an in-depth characterisation study of multiple sources of particulate was not within the scope of this research project. The use of one source of recycled rubber particulate controlled rubber shape as the same processing method was used to produce the particulate, but was not able to be varied. The findings of Chapter 3 concluded there was insufficient variability in composition of the supplied particulate for physical or mechanical properties to significantly vary the mechanical properties and behaviour of shockpads and therefore rubber type was also controlled but not able to be varied as part of this investigation. The rubber particulate was supplied in a 2 to 6 mm size range, consistent with literature review findings. The rubber could be sieved and recombined in different size ranges and size distributions and was therefore able to be both controlled and varied.

There are numerous binder manufacturers in the UK that supply moisture-curing polyurethane binders for shockpad construction. Binders are manufactured under controlled factory conditions and were considered from literature to be a product with little compositional variation for each manufacturer, however the effect of using binders from different manufacturers on shockpad mechanical properties was unknown. Binder type was therefore able to be controlled by using the same batch of binder from only one manufacturer and varied by using moisture-curing polyurethane binders from other manufacturers.

Design variables include shockpad thickness and binder content. Young (2006) had previously shown shockpad thickness in the range of 6 to 20 mm to have significant effect on shockpad mechanical properties. Thickness control was provided by the use of wooden moulds with a side height equal to the thickness required. The ability to change the side height of the moulds allowed shockpad thickness to be varied and the results of Young (2006) to be verified.

The binder content of cast in-situ shockpads can be controlled by the proportion of binder added to a set mass of rubber at the mixing stage of the construction process. As the viscosity of the binder varies with temperature, the method used on site where binder is poured from a vessel onto the rubber does not contain suitable control. A method where the rubber is weighed prior and post binder addition provides a method to control its content. Binder retained on mixing and compacting equipment was measured and considered insignificant. The ability to alter the proportion of binder to rubber mass allowed the effect of varying binder content to be investigated.

Cast in-situ shockpads were described in the literature review as being constructed by the mixing of rubber and polyurethane, compaction with an oscillating levelling beam and left to cure. Variables were identified in the mixing time of the rubber particulate and binder, the compaction levels of oscillating levelling beam and the temperature and humidity during cure. The unavailability of an oscillating levelling beam prevented large scale construction of shockpads with varying mix design from being constructed; however a smaller-scale construction method was developed to compact the rubber-binder mix into moulds. The method is described in detail in Section 4.2.5.

On site, rubber and binder is typically combined in an industrial-sized z-blade mixer. Optimal mixing time to ensure the rubber is evenly coated with polyurethane is suggested by binder manufacturers to be three minutes. For the purposes of the construction of small scale cast in-situ shockpads, the use of an industrial sized mixer was not practical and a small benchtop mixer considered more appropriate. Mixing time was able to be controlled through a timer and the rapid response of the benchtop mixer when switched on and off. The dissimilarity of mixing blade type and mixing action between the industrial and benchtop mixers does not allow a direct comparison of mixing time. As an examination of the effects of mixing time in the benchtop mixer was not directly comparable to those used for on-site shockpad construction, the variable was controlled but its effect on mechanical properties not investigated. The method used to determine the minimum mixing time required to produce thorough mixing of the rubber and binder is described in Section 4.2.5.

Shockpad bulk density is controlled on-site by the compactive force supplied by an oscillating levelling beam. The unavailability of an oscillating levelling beam required the use of hand-laying method for shockpad construction. There was no published information regarding the compactive forces or range of bulk density levels achievable for an oscillating levelling beam, so variations made to bulk density cannot be directly related to optimal, over and under-compacted shockpads produced on-site. However, bulk density was identified as a factor that affected the mechanical property of rebound resilience (Tipp and Watson, 1982) and was considered a key variable requiring further investigation in the literature review. Bulk density was able to be controlled by the addition of a constant mass of rubber-binder mix for a set mould volume. Variations were achievable by adjusting the ratio of rubber-binder mix added to the set mould volume. The development of the method used to compact shockpads is outlined in Section 4.2.5.

The outdoor location of cast in-situ shockpads subjects them to variable temperature and humidity conditions during their cure. Both temperature and humidity affect the cure rate of polyurethane binders which may affect the mechanical properties of the shockpad, however no data could be found in the literature review to quantify its effect. Temperature and humidity control of shockpads during cure was made possible by placing the shockpads in an insulated environmental chamber which remained at ambient conditions for the duration of binder cure. The unavailability of equipment to vary temperature and humidity prevented the effects of cyclic environmental conditions being examined as part of this investigation.

Each design and construction variable identified from the literature review and listed in Table 4.1 was able to be controlled and/or varied for the purposes of this investigation. A summary of the variables able to be examined as part of this investigation are listed in Table 4.2. These variables will be referred to collectively from this point as mix design variables regardless of their designation as constituent material, design or construction variables.

4.2.3 Benchmark Shockpad Development

The development of a benchmark cast in-situ shockpad provided a benchmark to measure the extent shockpad mechanical properties were affected by mix design variables. The benchmark shockpad was representative of current UK cast in-situ shockpad installations and was designed by assigning typical values to the mix design variables determined through a review of current practice. Three benchmark shockpads were produced to improve the statistical accuracy of the mechanical test results and to measure the standard variation of test results due to construction method variability.

Site-laid cast in-situ shockpad samples and mix design specifications (Table 4.3) were obtained from pitch constructors during the construction of two water-based hockey pitches. Shockpad samples were obtained by placing wooden moulds on the tarmacadam layer of the pitch construction and continuing over them with the oscillating levelling beam at the completion of laying a length of shockpad. The shockpads remained in the mould for several days until sufficient strength had been obtained for removal without damage. Mix design verification tests of bulk density and thickness were conducted on shockpad samples and rubber size and size distribution determined from rubber particulate collected from one shockpad construction were used for comparison with mix specifications and to determine typical values for variables, such as bulk density, which were not stipulated in specifications.

Bulk density measurements were used to determine the compaction levels of the rubber and binder in the shockpad. Mass per unit area is stipulated by sporting governing bodies as the standard test to measure compaction, however as discussed in the literature review, the measurement does not account for shockpads of different thickness. Bulk density measurements were therefore used in place of mass per unit area as they account for shockpad thickness. There is no standard test method published for bulk density measurements of shockpads. The developed bulk density method for shockpads involved the cutting of cylindrical cores 45 mm in diameter from random sections of shockpad samples.

Site-laid cast in-situ shockpads were characterised in terms of thickness and bulk density. Five cylindrical cores 45 mm in diameter were randomly cut from each shockpad. The diameter was not a standard size but the diameter of the only steel die available that was capable of cleanly cutting through shockpad samples. Three measurements of thickness and diameter were obtained using Vernier callipers for each core. Bulk density was calculated from the average values of thickness and diameter, given by Equation 4.1, and the results are listed in Table 4.3 together with average thickness of each core.

$$D_B = \frac{m}{t \times \pi \times \left(\frac{d}{2}\right)^2} \qquad \text{---------- Equation 4.1}$$

Where:

D_B	=	Bulk Density	[kg/m^3]
m	=	Core Mass	[kg]
t	=	Core Thickness	[m]
d	=	Core Diameter	[m]

Characteristics of site-laid shockpads were particularly useful for determining a benchmark value for bulk density, although it is not commonly specified or measured by industry or stipulated in publications by sporting governing bodies or Sport England. Tipp and Watson (1982) specify 700 kg/m^3 as a typical for the bulk density of shockpads, suggesting two shockpads with a bulk density of 410-470 kg/m^3 and 370-500 kg/m^3 were inadequately compacted. The bulk density measurements of the two characterised cast in-situ shockpads, shown in Table 4.4, were lower than that suggested by Tipp and Watson at 551.8 kg/m^3 and 568.1 kg/m^3. As the density of the two site-laid shockpads were so similar, this was considered typical of in-situ shockpad constructions and a round value of 550 kg/m^3 was specified as the industry standard value.

Both site-laid shockpads were taken from the construction of hockey pitches and a thickness of 12mm was specified for both. This thickness is typically used for hockey pitches and those intended for other sports typically employ shockpads with different thicknesses, so there is no industry standard thickness. The thickness for the standard shockpad used for this investigation was set at 12mm, with both thicker and thinner shockpads to be examined as part of the variation stage. Thickness measurements of the samples used to measure bulk density were taken using Vernier callipers and contained some variation from the specification. A figure of ± 2 mm considered a typical limit on variation through industrial collaboration.

Recycled rubber particulate reclaimed from worn truck and heavy duty vehicles was specified for both site-laid shockpads from which samples were taken. The literature review showed this rubber type to be typical of cast in-situ shockpads produced in the UK and that crumb is the typical particulate shape. Deriving measurements of rubber size and distribution from cured shockpad samples proved difficult. Specifications for the two site-laid shockpads stipulated a rubber particulate size of 2 to 6 mm, and through literature and industrial collaboration this value was confirmed as appropriate for use in the benchmark shockpad.

The particle size distribution for rubber particulate collected from the second shockpad construction site was measured and compared with the distributions measured for three different 25 kg bags of rubber particulate supplied for the construction of shockpads for this project, shown in Figure 4.2. The rubber size range is 1 to 4 mm, with the distribution showing a higher proportion of smaller sized particles around 1 to 2 mm in size. This does not match the specification of 2 to 6 mm size range supplied by the constructor and is therefore not a suitable distribution to base the benchmark shockpad on.

The particle size distribution of rubber particulate used to construct the benchmark shockpad was not able to be determined from specifications published in literature. Broad limits are placed on appropriate rubber particulate distributions for a particular size range used by the draft specification for characterisation of rubber particulate pr BS EN 14243:2002. The standard stipulates limits on proportions of rubber particulate outside of the specified size range but does not specify a well-graded distribution.

Recycled rubber particulate was supplied in 25 kg bags and subject to settlement of the smaller sized particles towards the bottom of the bag. To reduce the potential for variation in rubber size distributions produced by riffling rubber into the small quantities required for shockpad construction directly from the bags, the rubber was separated into its respective particle sizes and recombined according to a well-graded particle size distribution for the construction of benchmark shockpads.

Soil mechanics principles identified by Craig (1997) were used to develop a well-graded distribution for rubber particulate. Coefficients of uniformity (C_u) and curvature (C_c) are given by Equations 4.2 and 4.3 respectively. D values (10, 30 and 60) represent the corresponding particle size to the respective percent of rubber passing through a sieve read from a standard distribution plot of percent passing to particle size. For example, D_{10} represents the corresponding particle size when 10% of the rubber passes through the sieve, as shown in Figure 4.3. A higher coefficient of uniformity values represents a larger range of particle sizes and coefficient of curvature is required to be in the range of 1 to 3 for a well-graded distribution. The well-graded distribution for the benchmark shockpad was designed using requirements of coefficients of uniformity and curvature and is shown in Figure 4.2. A comparison of the particle size distribution for the benchmark shockpad and three bags of supplied particulate is also provided in Figure 4.2. The benchmark distribution is shown to be similar to the supplied rubber that is used in actual shockpad constructions.

$$Cu = \frac{D_{60}}{D_{10}} \quad \text{-------- Equation 4.2}$$

$$Cc = \frac{D_{30}^{2}}{D_{60} \times D_{10}} \quad \text{---------- Equation 4.3}$$

Where:

C_u	=	Coefficient of Uniformity	-
C_c	=	Coefficient of Curvature	-
D_x,	=	Particle Size Corresponding to x% Passing Through Sieve	[mm]

Moisture-cured polyurethane binders were specified for both site-laid shockpads from which samples were taken. Several different manufacturers produce suitable polyurethane binders and are all commonly used to construct shockpads in the UK. The manufacturer of the binder used in the first shockpad was unknown, therefore the binder used in the second shockpad construction was also used for the benchmark shockpad. Industry collaboration confirmed the benchmark binder to be commonly used for shockpad constructions in the UK.

The binder content of the two site laid shockpads are specified as 9 and 10% respectively. A minimum binder content of 5% is specified by Sport England (2003), however through industrial collaboration 5% was found to provide insufficient margin for error in binder distribution and typical values of binder content were in the region of 8-10%. In conjunction with site laid shockpad specifications, an average value of 9% binder content was established as appropriate for the benchmark shockpad.

Specification of a standard mixing time was developed from trials of mixing typical quantities of rubber and binder in the benchtop mixer. A visual inspection of the time required for the binder to fully coat the rubber was conducted and determined to be 3 minutes. This value of mixing time reflects mixing times stipulated by binder manufacturers and was therefore used in the design of the benchmark shockpad.

The design of the benchmark shockpad is summarised in Table 4.5. The mix design values were compiled from a combination of industrial collaboration, published literature and characterisation of site laid shockpads. A statistically more accurate quantification of the standard values for mix design variables produced on-site would have resulted from the characterisation of further site-laid shockpads. Attempts were made to source more shockpad samples, which included a letter to the Sports and Play Construction Association (SAPCA) to be distributed to its members, however, the unwillingness of many synthetic pitch constructors to allow their products to be tested anonymously for this investigation hindered the creation of an accurate picture of industry standard site-laid cast in-situ shockpads.

4.2.4 Mix Design Variable Ranges

The design of the benchmark shockpad provided a benchmark to measure the effect of changes to mix design on mechanical properties. Changes to the mix design were made with values higher and lower than the benchmark value to simulate the range achievable in site-laid shockpads. The effect of each variable was examined independently by ranging it through a series of suitable values, while all other variables remained constant at the benchmark value. An appropriate range of variation was determined for each mix design variable through consideration of literature and industrial collaboration. The range examined for each variable is listed in Table 4.6 and the development of suitable ranges for each variable is outlined below.

Size distribution for the benchmark, well-graded 2 to 6 mm rubber size range was determined from soil mechanics principles and the draft standard pr BS EN 14243:2002. The standard leaves substantial room for distributions to be used in shockpad constructions that do not have coefficients of uniformity and curvature that fit into the category of well-graded. The effect of using 2 to 6 mm sized rubber with distributions containing predominantly small and predominantly large sized rubber but remaining within the limits set by pr BS EN 14243:2002, were examined. A comparison of the predominantly small, predominantly large and well-graded rubber size distributions is given in Figure 4.3.

A rubber size of 2 to 6 mm range was specified as typical for cast in-situ shockpads constructed in the UK. Industrial collaborators also identified a 2 to 8 mm sized rubber that is sometimes utilised for shockpad constructions. The effect of changing from a typical 2 to 6 mm to a 2 to 8 mm rubber size was examined. The 2 to 8 mm rubber size was examined in three distributions as for the 2 to 6 mm rubber size. Similarly well graded, small and large size dominated particle distributions as the 2 to 6 mm rubber size were used. Distributions for 2 to 8 mm rubber were matched to the 2 to 6 mm rubber size by matching coefficients of curvature and uniformity to similar values and also fit the criteria of pr BS EN 14243:2002.

A value of 9% was determined as the benchmark value for the binder content of cast in-situ shockpads in the UK. The effect of reducing or increasing binder content from the benchmark was to be examined. Sport England (2003) recommend 5% as the lowest binder content to be used for shockpad constructions and provided the lower limit for examination in this investigation. The highest binder contents used for shockpad constructions published in literature were in the region of 17-20% (Tipp and Watson, 1982) which provided an upper estimate of binder contents used for shockpad constructions. Industrial collaborators agreed these values were unrealistically high, and upper limit for binder content would be more in the region of 15%. To create a good range of values a binder content of 12% was also considered as a high intermediary value.

Moisture-curing polyurethane binders were also considered from other major suppliers to the synthetic pitch industry. A further two major sources of polyurethane binder were supplied from different manufacturers, both of which are widely used to construct shockpads in the UK. These binders were of the same moisture-curing type as the benchmark value. As each manufacturer has several formations available for shockpad constructions, the manufacturer was asked to recommend the most suitable for standard UK weather conditions.

The thickness of shockpad layers can vary depending upon the sport for which the pitch is intended and to a lesser extent through undulations in the foundation layer. A thickness of 12 mm was considered to be the typical value of shockpad thickness and values either side of this was considered for the effects of undulations in foundations.

Through industrial collaboration a range of thickness from 8 mm to 15 mm was considered possible for a 12 mm shockpad. A thicker shockpad of 20 mm was also considered for sports such as football and rugby.

The range of bulk density achievable by onsite levelling beam was unknown and therefore could not be simulated by ranging values as part of this investigation. The limits were therefore set by the limits of hand-construction method. The lower limit was set by the bulk density of the rubber itself (density without any compaction) which is around 470 kg/m^3 (Charles Lawrence PLC, 2003). A value of 500 kg/m^3 was selected as appropriate to provide an example of an under-compacted shockpad. Trials deemed 600 kg/m^3 to be the upper value achievable with the manual compaction method and provided an upper limit of bulk density for this investigation.

4.2.5 Shockpad Construction Method

The following section contains a description of a method developed to produce cast in-situ shockpads in the laboratory. The shockpad construction method was required to a reproducible procedure that was capable of producing cast in-situ shockpads with a similar mix design to those produced by on-site. Through conducting trials, developments to improve reproducibility and reduce errors were made and a suitable method was developed. These developments, the final method and test methods used to verify the mix design of shockpads produced using this are described in further detail in the following sections.

4.2.5.1 Method Development

During the initial stages of method development, shockpads were constructed for the investigation into water based hockey pitches by Young (2006). The method involved adding binder to the rubber in set quantities and mixing until the rubber was adequately coated. The mix was transferred into moulds varying in height from 6 to 20 mm, compacted using a cylindrical bar rolled across the surface of the shockpad and left to cure in the laboratory.

This preliminary attempt at constructing shockpads provided a basic method that was capable of producing shockpads in the laboratory, but also highlighted many areas in the construction of shockpads that required careful control to ensure mix design specifications were met. An outline of the methods used for the control and variation of mix design variables were identified in Section 4.2.2. This section provides a more detailed description of the development process undertaken to control each mix design variable and reduce the potential for errors in mechanical property measurements. The process of the final shockpad construction method is shown schematically in Figure 4.5.

The use of moulds to contain the shockpads during construction and cure were considered imperative as they allowed thickness to be controlled and varied, provided a fixed volume for bulk density control and variation and also provided structural support to the shockpad during cure. The moulds were constructed from wood as they allowed easy fabrication and did not provide a strong bond with the polyurethane binder, allowing for easy removal of the shockpad after cure. A typical mould is shown in Figure 4.4, with wooden surrounds nailed to a plywood base. The internal dimensions of wooden surrounds were equal to the dimensions of the shockpad required, with surround height equal to shockpad thickness.

Shockpad bulk density and mould volume determined the mass of rubber and binder required to be placed into the mould for each shockpad. The total mass of rubber and binder required to be added to the mould is given by Equation 4.4. The mass of rubber was determined using Equation 4.5, taking into account the required binder content. Binder mass was determined from the difference of total mass and rubber mass and is given by Equation 4.6. The total mass of rubber and binder placed in the mould was constant for all shockpads expect variations in bulk density and thickness.

To ensure uniformity of rubber size distributions, rubber particulate was sieved into individual size classes and recombined in set mass proportions according to the specified rubber size ranges and distributions. Rubber particulate was randomly selected from the batch of recycled truck tyre rubber and sieved into their individual size classes using Endecott mesh sieves (150mm diameter) in a mechanical sieve shaker in the order specified in Table 4.7. Rubber particulate was placed in the sieve stack in 500g batches and shaken for 3 minutes. The rubber particulate was then removed from the sieves and placed in bags with rubber of the same size class.

$$m_t = BD \times V \quad \text{---------- Equation 4.4}$$

$$m_r = \frac{m_t}{\left(1+\frac{BC}{100}\right)} \quad \text{--------- Equation 4.5}$$

$$m_b = m_t - m_r \quad \text{--------- Equation 4.6}$$

Where:

m_t	=	Total Mass of Rubber and Binder	[kg]
m_r	=	Mass of Rubber	[kg]
m_b	=	Mass of Binder	[kg]
BD	=	Bulk Density	[kg/m^3]
V	=	Volume	[m^3]
BC	=	Binder Content	[%]

Some residual dust was retained on the particulate from the granulation process. The low strength dispersion bonds existing between the dust and particulate could affect the bonding between the particulate and polyurethane binder, potentially causing localised variations in bond strength. A high proportion of the residual dust was removed from the rubber by washing in cold water. The dust was collected by the water and when placed on a mesh grid inside a tray and oven dried at 70°C until there were insignificant changes in mass, the dust was collected in the tray below the mesh. Trials of this process showed sufficient dust could be removed by two cycles of this washing and drying process.

Clean and dry rubber particulate of each size class was weighed to the required proportion according to the total mass of rubber required. The proportion of rubber required from each size class was determined from the appropriate particle size distribution (Figure 4.3) and the total mass of rubber required which was calculated using Equation 4.5. A good distribution of the various size classes was achieved in trials by placing the rubber in a container with a lid and rapidly inverting the container five times.

Rubber particulate was placed in a stainless steel mixing bowl which was subsequently placed on an electronic mass balance. Binder was poured slowly onto the rubber until the required binder mass was achieved. The mixing bowl was placed on the mixing stand and the bowl set to a rotation rate of 18 RPM for 3 minutes (± 5 seconds). The mixing blades remained stationary as their lowest speed setting resulted in loss of rubber-binder mix from the mixing bowl.

Binder content was reduced at two stages of the shockpad construction process, residual binder remaining on equipment and on the wooden moulds. Binder was retained in the mixing bowl and on the spatula after the rubber-binder mix was transferred to the mould and on the rolling bar used to compact the rubber into the mould. An assessment conducted by weighing equipment before and after shockpad construction resulted in the binder content being reduced by less than 0.3% and was negligible for subsequent for shockpads constructed using the same equipment.

The rubber-binder mix was transferred from the mixing bowl to the mould with a plastic spatula. The mix was compacted by rolling a 50 mm diameter cylindrical steel bar along the top edge of the mould surroundings in one direction and then in the perpendicular direction and repeated until the surface of the shockpad was flat. Rolling in perpendicular directions was shown in trials to provide a smoother surface than just rolling in one direction could provide. The use of a cylindrical bar to roll the surface flat was considered to produce a more even pressure than manual vertical tamping, therefore producing a more even compaction and bulk density across the shockpad. Bulk density measurements of sections of shockpad taken during trials showed the cylindrical bar to be a suitable compaction method.

Immediately after construction, the shockpads were placed in an insulated environmental chamber where temperature and humidity levels remained at ambient levels. After 14 days the shockpads were considered to have reached full cure and were removed from the moulds by removing the surrounds and separating from the base with a metal spatula. There was minimal adherence between the binder and wooden mounds and the shockpads were easily removed with minimal damage.

The bleeding of binder onto the mould was difficult to quantify as it altered depending on the mix design of the shockpad, particularly with binder content and rubber particle size and distribution. An assessment from the construction of small scale shockpads and weighing moulds before and after construction identified the 5% binder content shockpad required 2% (of total binder mass) extra binder to be added. The benchmark shockpad required 5% extra binder and 10% and 16% extra binder for the 12 and 15% binder content shockpads respectively. The actual binder content of the shockpads produced could not be verified as there was no suitable test method available.

4.2.5.2 Mix Design Verification

A series of verification tests were conducted on cured shockpads to ensure the mix design variables listed in Table 4.1 had met specifications. The bulk density and thickness measurements used to determine the mix design of cured shockpad collected from site (detailed in Section 4.2.3) were repeated on shockpads produced using the developed construction method.

Bulk density was verified through the measurement of thickness, diameter and mass of 5 cores taken randomly across the section of shockpad available for destructive testing. Vernier callipers were used to measure the dimensions of thickness and diameter; however some error was incurred due to the easily deformable nature of shockpads. This error was reduced by recording dimensions with a minimal force applied to the callipers. Three measurements were taken for each dimension and the mean value recorded for each. Equation 4.1 was used to calculate mean bulk density from the dimensions of thickness, core diameter and core mass for each sample.

Thickness measurements were taken from the five cores used to measure bulk density and the five samples to be used for tensile measurements. Three readings were taken from each sample resulting in the thickness measurements being calculated from a mean of 30 measurements of the destructive test area. A similar issue with dimensional errors due to the deformable nature of the shockpad was present as for measurements of bulk density.

An average of bulk density and thickness verification measurements for the three benchmark shockpads are provided in Table 4.4. Measurements compare well with the benchmark values of 550 kg/m^3 and 12 mm for bulk density and thickness respectively, showing an accurate and repeatable method had been developed.

A lack of available test procedures prevented verification of other mix design variables. These variables included binder content, rubber size, rubber size distribution and mixing time. The measures put in place to carefully control these variables during the construction process were considered sufficient in ensuring mix design specifications would be met.

Binder content was verified by weighing moulds before shockpad construction and after shockpad removal to determine the quantity of binder lost to the mould. However, a method to measure binder content for site-laid shockpads was of particular interest to the sports surface construction industry. There is not provision of weighing moulds on site before and after construction to determine the actual binder content of shockpads and currently tensile strength was being used as an indirect indicator of binder content.

An attempt was made to develop a method to measure the binder content of cured shockpads. The initial method for binder content measurements involved the construction of small shockpads with a range of known binder contents. The shockpads had a known rubber mass, were weighed post construction to measure binder mass and were cured on plastic sheeting to prevent any binder loss. Samples of each shockpad (10g) with known binder content were immersed in dimethylformamide (DMF), a solvent, to dissolve the polyurethane network and leave the rubber intact. As the polyurethane formed irreversible crosslinks upon curing, it could never be completely dissolved into the DMF, however initial tests showed the polyurethane network was destroyed after 24 hours of immersion with mild agitation at 40°C. Some polyurethane remained attached to the rubber and could not be removed by the DMF even after prolonged immersion.

A second stage to the test method was added to remove the residual binder from the rubber. After immersion in DMF, the rubber was washed in distilled water and dried and then immersed in toluene at 40°C with mild agitation. The second stage was added to produce swelling in the rubber, therefore releasing the attached polyurethane. However, after prolonged immersion in toluene a small amount of polyurethane remained on the rubber surface, which for the small sample size produced significant errors. The toluene also had the effect of removing significant proportions of plasticisers and extender oils from the rubber, reducing the mass of the rubber and therefore increasing the measured binder content. The method at this preliminary stage was unsuitable for measuring binder contents to the accuracy required. The method could not be used as a viable method to verify the binder content of the shockpads at this stage in its development.

The results of verification testing are provided in Table 4.8 and show the average values for thickness, bulk density and binder content measurements fell within limits of ± 1 mm, ± 20 kg/m^3 and ± 1% for each test respectively. The shockpads constructed were deemed to sufficiently match mix design specifications and were therefore suitable for mechanical testing. It was noted from the verification results that some recovery of the rubber occurred when compacted into the mould. This produced shockpads which were all slightly above the specified thickness and therefore slightly reduced bulk density. It is anticipated for future work that the mould be constructed slightly below the required thickness to account for rubber recovery.

4.2.5.3 Shockpad Size

The shockpad size used was 900 mm by 300 mm and is shown in Figure 4.6. Each shockpad constructed required sufficient area for each destructive and non destructive test. Non destructive tests such as Berlin Artificial Athlete, Clegg Hammer impacts and ball rebound measurements were conducted on the same test piece. The same section was also used for later force plate testing in Chapter 5 of this thesis. The shockpad sample was required to be the same size as the force plate, 600 mm by 300 mm, and so dictated the size of the non-destructive test section. This size was also deemed sufficiently large in preventing edge effects during the mechanical impact tests.

Destructive tests, such as tensile strength, cyclic fatigue and mix design verification measurements required a section of shockpad that could not be used for any further testing once samples had been cut. Five tensile samples (150 mm by 25 mm), five cylindrical samples for mix design verification (45 mm in diameter) and one square cyclic fatigue sample (150 mm square) were required from the destructive test area. Some extra area was provided for contingencies, but making the shockpad much larger than was required was wasteful as considerable quantities of time were required to separate the rubber into individual particle size classes. A 300 mm square section was provided for these destructive tests.

4.2.6 Mechanical Test Methods

The following section describes the test methods used to measure the mechanical properties of shockpads and shockpad carpet systems. Each mechanical test is used to measure performance according to the functional requirements of shockpads and whole pitch constructions identified in the literature review; ball interactions, player interactions, environmental and mechanical durability and safety during head impacts. Overall pitch performance is determined by each fundamental requirement, and changes in mix design may, for example, result in higher ball rebound heights and a less compliant pitch. These mechanical tests were firstly conducted on the shockpad layer to examine the effect of mix design for the shockpad layer alone and then repeated for a composite system of shockpad and carpet to indicate the effect of shockpad mix design on overall pitch performance. The carpets used for composite structures are described in 4.2.8.

The literature review revealed few standard mechanical test methods stipulated by sporting authorities for the shockpad layer of the pitch construction and required some tests used to measure whole pitch performance to be adapted for use on the shockpad alone. The standard test methods used were Berlin Artificial Athlete for player interactions, ball rebound for ball interactions and tensile testing for durability. Mechanical test measurements of safety during head impacts were not examined as part of this investigation. The IRB, who are the only sporting governing body to stipulate this test, do not provide realistic limits of critical fall height as discussed in the literature review. Reasoning for the low critical fall height, provided by Shorten and Himmelsbach (2002), was attributed to the detrimental effect high critical fall heights had on player and ball interactions that could render pitcher for some sports unusable. Player and ball interactions were considered paramount aspects in the usability of a pitch, therefore the compromises that might be required for a not widely stipulated test were not considered to be useful to the outcomes of this project.

The standard industry tests used to determine the mechanical properties of shockpads were the Berlin Artificial Athlete for athlete interactions, ball rebound for ball interactions and the tensile test for durability. The suitability of these standard test methods have been criticised in literature. Therefore, the Clegg Hammer was trialled alongside the Berlin Artificial Athlete as an alternative test method for player interactions and a cyclic fatigue test developed and trialled as an alternative to the tensile test. Both tests offered improvements over the industry standard methods and an assessment of their suitability is provided in the discussion section of this chapter.

Berlin Artificial Athlete, Clegg Hammer and Ball rebound tests were all non-destructive test methods and all conducted on the same test piece. Ball rebound tests were conducted first as it was a lower energy test than the player interaction tests, followed by the Berlin Artificial Athlete and finally the Clegg Hammer. Tests were conducted in this order to prevent any damage produced by the player interaction tests affecting the results of ball interaction tests. However, upon inspection of each shockpad following Berlin Artificial Athlete and Clegg Hammer tests, no visible damage could be seen in test locations. Clegg Hammer and ball rebound tests were conducted at three central locations on the shockpad to avoid edge effects. The Berlin Artificial Athlete test was conducted in the centre of the sample only due to the size of the device. Trials to measure the repeatability of each test at the same test location on the benchmark shockpad showed differences in readings varied from the average by 1% for the Berlin Artificial Athlete, 10 g's for the Clegg Hammer, 1 cm rebound height for the vertical ball rebound test and 20 kPa for the tensile test. As the cyclic fatigue test remains under development, repeatability testing remains to be conducted.

4.2.6.1 Vertical Hockey Ball Rebound

The vertical ball rebound test measures rebound resilience and is stipulated in performance standard documents by the FIH (1999), FIFA (2006) and the IRB (2006). Sporting governing bodies utilise the ball rebound test to measure the ball interaction characteristics of whole pitch constructions together with a ball roll tests across the surface of the pitch. As the ball rolls across the surface, interaction is with the carpet layer only and measurements are not influenced by the shockpad layer below. Therefore, for the purposes of this investigation only the vertical ball rebound test was used to measure the changes in ball interaction behaviour.

It is expected that the rebound resilience of shockpads would differ for impacts of a hockey ball and football. Firstly, standard test requirements for football (FIFA, 2005; UEFA, 2003) and rugby (IRB, 2005) require a 2m ball drop height and hockey (FIH, 1999) requires a drop height of 1.5m, therefore providing different impact energy. Secondly, the different shape and contact area would produce different interaction characteristics and therefore affect rebound height. The use of a football to measure the effect of shockpad variations on the rebound resilience of football and rugby pitches introduces further variations due to ball pressure and shape. The rigid hockey ball was therefore used for all vertical ball rebound tests.

Young (2006) conducted vertical ball rebound tests using a hockey ball dropped by hand and a visual method to measure ball rebound heights against a surveying staff. Young (2006) found this method to provide satisfactory accuracy in ball rebound measurements but did contain an element of human judgement. Trials of the ball rebound method found the elements of human error could be reduced for both the drop and rebound measurements. A repeatable drop height was achieved by fixing a rigid cantilevered beam to the surveying staff at a height of 1.57 m. The diameter of the ball was measured to be 0.07 m, therefore placing the top of the ball against the underside of the beam produced a constant drop height of 1.5m for the bottom of the ball. Ball rebound height measurements were recorded using a digital video camera and compared to visual measurements. The average for visual measurements were within 1 cm of those measured by the digital video camera and was therefore deemed sufficiently accurate.

The vertical rebound resilience of shockpads was determined using Equation 4.7. A standard Kookaburra Dimple Elite Mark II (FIH approved) hockey ball was dropped from the height of 1.5m according to FIH standards (1999). The ball rebound height was measured visually using a surveying staff with 1 cm gradations. Five drops at each of three locations on the shockpad were used to determine the rebound resilience of each shockpad and the extent of its variability.

$$R = \left(\frac{H_r}{H_d}\right) \times 100 \quad \text{------- Equation 4.7}$$

Where:

R = Rebound Resilience %

H_r = Rebound Height [m]

H_d = Drop Height [m]

4.2.6.2 Berlin Artificial Athlete

The Berlin Artificial Athlete (BAA) was used to simulate the heel strike of a player during running and is stipulated by FIH (1999) for hockey pitches, the IRB (2005) for rugby pitches and FIFA(2005), UEFA (2003) and the FA (2005) for football pitches. The test measured a value of force reduction by comparing the reaction force of the surface to the reaction force of rigid concrete surface. The standard reaction force for the rigid surface was measured as 6600 N prior to testing shockpads. This constant value of was used for all force reduction calculations given by Equation 4.8.

Three impacts were conduced at each of three locations on the shockpad. Standard procedure was followed by discarding measurements for the first drop due to the initial compaction of the shockpad and the average force reduction for each location calculated from force reduction measurements for the second and third drops.

The raw measurement of force against time obtained by the BAA is filtered to unwanted remove noise produced largely by the inertial movements of the weights and their frame. Each sporting authority stipulates different filter parameters which smooth the trace and produce different peak impact force values. BAA measurements taken as part of this investigation use a general European Standard (CEN) sports surface filter, which is a second order Butterworth type filter with a cut-off frequency of 120 Hz.

$$FR = \left(\frac{F_r - F_s}{F_r} \right) \times 100 \quad \text{----------} \quad \text{Equation 4.8}$$

Where:

FR	=	Force Reduction	[%]
F_r	=	Reaction Force on Rigid Surface	[N]
F_s	=	Reaction Force on Shockpad	[N]

4.2.6.3 Clegg Hammer

The Clegg Hammer was originally developed for measuring the stiffness and strength of soils and soil-like materials. Young (2006) showed correlations between force reduction measurements from the Berlin Artificial Athlete and peak deceleration measurements from the 2.25 kg Clegg Hammer for water based hockey pitches. These findings suggest the Clegg Hammer test may offer a suitable test for measuring athlete interactions for shockpads which is lighter and more portable than the Berlin Artificial Athlete.

Trials were conducted to determine the suitability of the Clegg Hammer test for shockpads. Issues such as friction from the falling weight through the guidance tube and uneven impacts were raised by Carré et al (2004) as potential factors which could influence measurements. The amount of time allowed between impacts at the same location was also observed during trials to influence measurements due to the extent of shockpad recovery. These issues were overcome by reproducing rapid impacts on each location to minimise shockpad recovery and observing excessive interference of the falling weight by the guidance tube though the distinctive sound that it produced. Measurements where excessive interference from the guidance tube occurred reduced as experience using the Clegg Hammer was gained. In the rare occurrence where excessive interference did occur these results were discarded and the location retested.

The standard method for soil impacts, outlined by Young (2006), was used to measure the peak deceleration of the 2.25 kg Clegg Hammer on shockpads. Impacts were produced by lifting the hammer to a height of 45 cm and dropping it through a guidance tube onto the shockpad. A reading of hammer peak deceleration, termed Clegg Impact Value (CIV), was output from an accelerometer contained in the hammer (in gravitational units) to a hand-held device.

The average CIV and its variability were determined by five drops at three locations on the shockpad, which is standard procedure for the Clegg Hammer test. The first drop at each location was discarded as a lower CIV value is recorded due to the initial compression of the shockpad. The average CIV and standard deviation for each location was determined from the final four drops at each location which produced similar measurements in comparison to the first reading.

4.2.6.4 Tensile Strength

Tensile strength measurements are used within the sports surfacing industry to indirectly assess shockpad durability. In-service shockpads generally experience only small quantities of tension as a component of shear stresses applied by stopping and turning movements of players and ball impacts and no basis for a relationship between shockpad tensile strength and durability has been published. It is currently the only established test to measure shockpad durability and so was used as part of this investigation.

Tensile samples were cut using a steel die in a hand operated press to dimensions given in BS EN 12230:2003. Each sample was carefully inspected for imperfections in the rubber packing as they were found in trials to produce areas of higher stress concentration which resulted in low tensile strength measurements. Vernier callipers were used to measure dimensions at three positions and the average reading recorded. Samples were placed in a Lloyd tensometer and tensile force applied at a rate of 50 mm/min. Measurements of force and extension were recorded by the tensometer and output into a graphical format by an interfaced computer. All tests were conducted in ambient laboratory conditions between 18 and 22°C.

A typical force-extension graph used for tensile measurements is shown in Figure 4.7. The graph shows the shockpad being loaded to a peak force and subsequent drops in force occurring as a tear runs through the tensile specimen at the failure point. Failure was said to occur once the peak force had been reached as the subsequent reduction in force was due to damage in shockpad integrity. Peak force measurements were converted to stress according to Equation 4.9.

$$\sigma_t = \frac{F}{t \times w} \quad \text{-------- Equation 4.9}$$

Where:

σ_t	=	Tensile Strength	[Pa]
F	=	Force at Failure	[N]
t	=	Sample Thickness	[m]
w	=	Sample Width	[m]

4.2.6.5 Cyclic Fatigue

The literature review showed shockpad durability to be a measure of its resistance to both mechanical and environmental degradation. The tensile strength test is the current method stipulated by FIFA (2005) and UEFA (2003) to provide an assessment of durability for shockpads, with FIFA (2005) requiring a minimum strength requirement of 0.15 MPa.

The tensile test provides the application of a relatively rapid tensile load to failure, and therefore a measure of the bond strength between the rubber and binder contained in a shockpad. If the shockpad meets the minimum requirements of tensile strength it is deemed to provide adequate durability for a standard shockpad lifetime of at least 7-8 years (Fleming et al, 2002). Within the industry, a shockpad is deemed to have failed when significant proportions of rubber have become separated from the polyurethane network at the surface of the shockpad. The tensile test was criticised in the literature review as an unsuitable test for measuring shockpad durability as real shockpad degradation is not simulated by the rapid catastrophic failure across the entire shockpad cross-section that occurs in tensile tests. Mechanical and environmental degradation of in-service shockpads results in a reduction in the rubber-binder bonds due to binder degradation and fatigue from repetitive strain cycles and may also lead to excessive changes in mechanical properties.

Mechanical degradation was shown in the literature review to be produced by compressive and shear forces from player and ball impacts. The majority of movement on a pitch was shown to be standing, walking and slow jogging; which were all shown to contain only small horizontal components through force plate testing. Such movements contained only a small tensile component and therefore this type of degradation was not well represented by the tensile test. Further to this, the effects of water flow through the shockpad and the cyclic moist-dry environment of the rubber and binder are also not simulated.

A mechanical cyclic fatigue test was hypothesised to provide a more accurate simulation of in-service impacts and therefore provide a quantitative value for shockpad durability. The test was developed to provide a continuous cycle of compressive shear force to the shockpad simulating the impacts from the heel strike of a player. There were numerous methods for simulating heel strikes considered during the development of this test programme, such as using a hemispherical indenter in the shape of the heel, which would introduce both compressive and tensile forces into the shockpad. However, upon further consideration the factors of footwear and the carpet layer were considered to produce an area load over a section of shockpad with the possibility of abrasion from the carpet layer. It was therefore concluded flat-faced shear plates would produce a satisfactory representation of a player's heel.

The aim of the test was to artificially degrade the shockpad over a short time period and quantify durability through the number of cycles required to cause failure. Mechanical tests and mass loss measurements would be conducted at periodic intervals during the cyclic fatigue testing to indicate mechanical failure through both changes in mechanical properties and breakdown of the rubber-binder bonds to cause loss of the rubber particulate. The effects of environmental degradation were not considered in the initial development of the test method as it proved more difficult to simulate. However, the option to add an environmental element to the test method was available during the later stages of development if the preliminary tests were deemed suitable. During these preliminary stages of development only selected shockpads were tested. Varying binder content and thickness were seen to produce the largest changes in tensile strength. Therefore the limits for the range for each shockpad type were tested (5 and 5% binder content and 8 and 20 mm thickness) together with a benchmark shockpad to determine the sensitivity of the test method.

The test aimed to simulate shockpad degradation in high-use areas of the pitch. Each testing run simulated the number impact cycles a small section of pitch in a high-use area would receive in one year. Mechanical testing and mass loss tests conducted between each testing run to determine changes in shockpad mechanical properties and loss of rubber after each simulated yearly period. Conducting, for example, eight test runs would show the mechanical property changes and rubber loss over an eight year period. The amounts of literature from various biomechanical and sport-related sources was limited and the number of cycles required for each test run was determined by combining information for different field sports. A general relationship for the number of impact cycles a small pitch section will experience per year of use is given by Equation 4.10. This breaks the impacts up into impacts per hour, number of hours a pitch receives a week and the number of weeks in a year a pitch is used. The advantage of using Equation 4.10 is that the number of cycles used to simulate the number of impact cycles per year can be adjusted for each shockpad test according to anticipated pitch usage. However, for the purposes of the method development and durability testing of the shockpad produced a value of cycles per year was required to be determined.

$$\frac{cycles}{year} = \frac{impacts}{hour} \times \frac{hours\_used}{week} \times \frac{weeks}{year} \quad \text{------- Equation 4.10}$$

High use areas of the pitch, such as goal mouth, have a proportionately higher number of impacts per hour than lower use areas, and so will degrade at a faster rate and fail first. The number of cycles a section of pitch received a year appears to have limited research. Data presented in the literature review showed the travel of one player across a football pitch during 45 minutes (Figure 2.4). Enlarging this figure into A3 size and placing a 2 mm grid across the pitch surface, the pitch could be broken into sections. One impact was assumed to occur in each grid section for each line of travel passing through. The highest number of impacts for one grid section was seven impacts over a 45 minute period. Assuming each player covers the same area of the pitch, which is unlikely due to the different positions of players within a team, but necessary due to a lack of literature based upon the pitch coverage of other members of a team, the number of impacts per hour for the highest use areas of the pitch is determined using Equation 4.11. It is also assumed that the opposing side mirrors the movement on the opposite side of the pitch for that 45 minute period and the movement for both teams is the same but mirrored on the opposite side of the pitch for the following 45 minute half. Due to a lack of similar literature for the game of hockey and rugby, movements are assumed to be the same for all sports.

$$\frac{\text{Im}\,pacts}{hour} = \left(\frac{impacts}{45\text{min}} \times \frac{2}{3}\right) \times 11 players \times 2 teams \times 2 halves \quad \text{------} \quad \text{Equation 4.11.}$$

The amount of usage a pitch receives a year will vary. Young (2006) lists the usage of high-level hockey pitches as between 50 to 75 hours per week and community football pitches constructed with the assistance of the Football Foundation (2004) required a minimum of 85 hours of use per week. This usage includes games and training, which will utilise different areas of the pitch to different extents, but as literature showing how the pitch is used differently and for what proportions of time, it is assumed that the same areas are used for games and training. An average of 75 hours per week was selected as a middle ground between high-use community pitches and lower use specialised water based pitches. The number of weeks a pitch will be in use is dependent on its use and whether it is for community use, schools use or high-level sports. A pitch may be used less in the off-season or during holidays and so with 52 weeks in a year a pitch it is assumed a pitch will receive the equivalent full use for about 45 of these.

The number of impact cycles an average shockpad in high-use areas of the pitch was calculated using Equation 4.10. The number of impacts per hour was determined using Equation 4.11 and a value of 9 impacts over a 45 minute period, which equated to 205 impacts per hour. Pitch use for 75 hours per week, 45 weeks of the year resulted in 692 000 impact cycles from players per year on a high-use section of shockpad.

Mechanical degradation of a shockpad is mostly constituted of foot strikes from players and ball impacts and the higher energy of the foot strike impact would be expected to produce significantly more degradation than the lower energy ball impact. Accordingly each cycle of the fatigue test was required to simulate the magnitude, direction and contact time of a typical foot strike onto the shockpad surface through a sine wave. However, data gathered in the literature review showed each movement, the velocity of the movement and the mass of the player produces different vertical and horizontal loads, making the identification of typical load magnitude, the angle of the resultant shear loads and contact time difficult to assess.

The magnitude and angle of impact loads produced by players was shown to be particularly dependent on movement action and body mass in Table 2.2 of the literature review. Adrian and Xu (1990) and Blackburn et al (2005) were the only researchers to provide comprehensive magnitudes for vertical and horizontal force and contact time. These results were used to develop vertical forces, horizontal forces, shear angle and contact time for the simulated impact cycle, as shown in Table 4.9. The data presented by Adrian and Xu (1990) was in units of body weight and was therefore required to be converted into unit of force. Impact force is a product of body weight, gravity and force for vertical force and horizontal forces in the aft-fore and medial-lateral directions. Body weights vary significantly between children and adults and also among players of different sports. Rugby players were shown in the literature review to have an average mass of around 90 kg which would represent the upper limits of body weight. Therefore a body weight of 75 kg was selected to represent a typical adult or teenager for the purposes of this investigation.

Vertical forces ranged from around 1000 to 3250 N and horizontal forces from 0 to 2000 N for various movements. Movements producing high vertical and horizontal forces and particularly a high ratio between them are expected to increase mechanical degradation of the shockpad, for example the movements of cutting and veering. Therefore, the worst case of a high number of veering movements as may occur in a game of rugby was selected for peak vertical and horizontal movements of

1800 and 250 N respectively. In-service the magnitude of forces experienced by the shockpad would be reduced by the carpet and in-fill materials directly above. The magnitude of the transferred load would be dependent on the type of carpet and in-fill material and the age of the carpet. No published data quantifying the proportion of load transferred to the shockpad could be found in the literature and therefore could not be estimated. The worst case of a worn carpet and compacted in-fill was taken and full transference of force was assumed.

The contact time of a typical athlete foot strike was required to determine the frequency of the sine wave for each cycle. The contact time for various movements identified in the literature review is shown in Table 4.9. Contact times vary between 0.2 and 1.1 seconds. An average value of around 0.5 sec was assumed for contact time which included loading from the heel, rolling forward through the mid-foot and push off from the toes. This equates to a frequency of 2 Hz.

Accelerated mechanical degradation was applied to shockpad samples by a Dartec cyclic fatigue machine. The machine was able to simulate the impact of a foot in a sine wave form. Shear plates were used to transfer vertical force applied by the machine into vertical and horizontal force components to simulate the typical foot impact. The plate angle required to provide the correct ratio of vertical to horizontal force was calculated using Equation 4.12. Values for vertical force and horizontal force determined during the test method development determined plate angle to be 22 degrees. The resultant force (R) required to be applied by the cyclic fatigue machine to achieve vertical and horizontal force components is given by Equation 4.13. Using the same values of vertical and horizontal force as plate angle a resultant force of 1817 N was calculated.

The shear plate set-up with the shockpad and horizontal and vertical force components is shown in Figure 4.8. The plates were constructed from steel, had a square surface area of 10 cm and weighed approximately 3 kg. The self weight of the top shear plate produced a 30 N static load on the shockpad samples, however as this represented only 1.8% of the resultant force applied during each cycle, it was considered negligible. Shockpad test samples were cut into 10 cm square sections to fit the size of the shear plates. Medium grade sandpaper was adhered to both faces of the shear plates to avoid movement of the shockpad during cycling and to simulate mechanical interlocking with the carpet layer. Initial testing of the machine set-up with horizontal deflection transducers showed no movement of the plates in the horizontal direction during a trial run over 100 000 cycles.

$$\theta_1 = 90 - \tan^{-1}\left(\frac{F_V}{F_H}\right) \quad \text{------- Equation 4.12}$$

$$R = \sqrt{F_V^2 + F_H^2} \quad \text{--------- Equation 4.13}$$

Where:

θ_1	=	Plate Angle	[degrees]
F_V	=	Vertical Force	[N]
F_H	=	Horizontal Force	[N]
R	=	Resultant Force	[N]

The Dartec was setup using the parameters determined during test method development, listed in Table 4.10. The sine wave pattern produced by the machine to simulate each cycle using the input parameters is shown in Figure 4.9. Force and deflection data output by the Dartec was recorded via a data logger in sampled lots using a programme created using Fieldview. Samples of data were taken in over 5 second periods in 10 minute intervals for each run of 692 000 cycles which represented one year of impacts. Vertical deflection data output by the Dartec was compared to deflection data collected by a linear variable deflection transducer (LVDT) to verify outputs of the Dartec only and was not used further to quantify changes in shockpad properties. The machine set-up is shown in Figure 4.10. Eight test runs were conducted for each sample, representing eight years of degradation. Shockpad samples were not tested to full failure due to the time consuming nature of the cyclic fatigue method.

Following each test run, a 15 minute period was allowed for the shockpad to recover before any mechanical testing was conducted. This recovery time was determined to as necessary though preliminary testing, as shockpad thickness was shown to increase towards its original value and reach a plateau after around 10 minutes. An additional 50% was added to recovery time to ensure full thickness recovery had been reached.

Following the recovery time tests were conducted in the following order: Mass, thickness, ball rebound, Clegg Hammer and then mass loss was re-measured. Tests were conducted in this order to ensure rubber particulate lost from the sample was due to the cyclic fatigue and not the mechanical tests. Mass loss tests were conducted to indicate shockpad failure through breaking of the rubber-binder bonds and rubber being lost. Mass was measured by weighing the sample on an electronic mass balance correct to three decimal places.

Mechanical property tests were conducted to quantify the changes in mechanical properties with degradation. The mechanical tests included the ball rebound test described in Section 4.2.6.1 to simulate changes in ball interactions. The small size of samples provided insufficient self-weight to prevent upward movement due to inertia during the ball impact. Weights (1 kg) were placed on each corner of the sample to prevent movement during the impact. Some edge effects may have been produced by the use of weights, however, similar values were achieved as for the larger sections of shockpad and therefore considered acceptable. The Clegg Hammer test described in Section 4.2.6.3 was used to measure changes in player interactions. The Clegg Hammer was the only method able to be used to measure player interaction as the foot size of the Berlin Artificial Athlete was too large for the sample size. Thickness measurements were taken using Vernier callipers to determine if mechanical property changes were a result of thickness reduction in the shockpad, changes in constituent material properties or internal movements within the shockpad.

4.2.7 Cure Time of Shockpads

The polyurethane binder used to construct shockpads for this investigation was cured by atmospheric moisture over time. The binder rapidly gains strength initially to bind the rubber particles together, but continues to reach full cure over a period of years. A realistic cure time for shockpads constructed for this project was required to be determined to ensure sufficient strength had been reached for binder cure state to not significantly affect mechanical test results.

The cure time of shockpads was measured by constructing four shockpads with the same mix design, construction method and cure environment as the benchmark shockpad. The increased or decreased thickness of the binder coating resulting from changes in binder content or rubber size and its distribution were considered to affect the binder cure rate by a negligible amount. Clegg Hammer, ball rebound and tensile tests were conducted to determine the change in mechanical properties in 24 hour intervals over a period of 14 days.

Mechanical test results (Appendix 1) showed a sufficient plateau in all mechanical properties had been reached after a 14 day period. The small changes in binder cure state that occur after the 14 initial cure period were considered to present minimal error to mechanical tests conducted on different days or in the future. Shockpad samples retained and stored in ambient laboratory conditions to allow further testing to be conducted at a later date to observe changes in mechanical properties of shockpads over a period of years.

4.2.8 Effect of Carpet and In-fill Systems

The mechanical testing of shockpad layers indicated how changes to mix design affected aspects of player and ball interactions and durability. The addition of the carpet layer over shockpads has been shown to affect shockpad mechanical properties and behaviour (Walker, 1996; Young 2006) and therefore requires investigation to provide an understanding of how shockpad mix design changes will affect mechanical properties of the whole pitch.

A multitude of different carpets are commercially available for synthetic pitch construction and testing all in combination with shockpads of different mix design is unrealistic. Two of the most common pitch types currently being constructed in the UK that are water-based hockey pitches and 3rd generation pitches for football and rugby. Multi-use games areas are also commonly constructed for schools and community use. These synthetic pitches are allowed a wider range for pitch performance characteristics, therefore requiring less precision in shockpad performance and so were not considered within the scope of this investigation.

The carpets for water-based hockey pitches and 3rd generation pitches differ substantially. Water-based carpets have short pile which is watered prior to play, while 3rd generation carpets have a much longer pile which is filled with sand and rubber particulate and there are numerous variations of each carpet type available commercially. Through industrial collaboration, one common water based carpet and one 3rd generation carpet were selected from leading manufacturers. The specifications for each carpet are provided in Table 4.11, where they are designated as generic water based carpet and generic 3rd generation carpet.

A sample of water-based carpet measured 300 mm by 600 mm and was the same size as the shockpad sample. The carpet sample was unused which simulated a new pitch construction. The hockey carpet was not watered as it would be under normal playing conditions to eliminate variability of results due to drying of the carpet during testing. The 3rd Generation carpet measured $1m^2$ (larger than the shockpad) and had been rolled 50 times to compact the in-fill and simulate a slightly worn-in pitch as stipulated by FIFA (2005).

Shockpads were placed on the rigid concrete floor and the carpet layer placed above in the configuration shown in Figure 4.11. All mechanical tests conducted on the shockpads (with the exception of cyclic fatigue) were repeated for the shockpad-carpet system. During preliminary mechanical testing, the carpets were observed to possess sufficient self-weight to prevent carpet movement due the inertial effects of the mechanical tests and therefore did not require restraint or bonding to the shockpad. Vertical hockey ball rebound drops were conducted for the water-based carpet only and not on the 3rd generation carpet as the low energy impact of the hockey ball was absorbed by the carpet and rubber and sand in-fill and not affected by the shockpad. Such results were also not relevant as 3rd generation carpets are not suitable for hockey.

4.3 Mechanical Properties of Shockpads

This section presents the results of mechanical property testing on shockpads with mix design variations. A test programme was devised to design a benchmark shockpad and examine the effect of independently varying shockpad thickness, binder content, bulk density, binder type and rubber size and size distribution over a range of values on the mechanical properties of shockpads. A method was developed to facilitate the construction of cast in-situ shockpads with mix design variations on a small-scale in the laboratory, which was verified as being sufficiently accurate and repeatable through trials. Mechanical tests were repeated on two generic shockpad-carpet systems, water based and 3rd generation, to measure the effect of shockpad mix design variations for whole pitch constructions.

The mechanical test methods were selected from current industry standard test methods for shockpads and whole pitch constructions identified in the literature review. The mechanical tests were selected to measure the response of each shockpad to the functional requirements of shockpads; ball and player interactions and durability. Industry standard test methods for measuring player interactions and durability were criticised in literature for their inability to accurately simulate in-service conditions. Therefore, alternative mechanical test methods were developed and evaluated alongside standard tests as part of this investigation to offer improvements in the testing of shockpads.

Ball interaction tests measured the rebound resilience of a vertical hockey ball impact, where a decrease in rebound resilience measurements translates to decreased ball rebound heights. Ball interaction tests were conducted on shockpads and shockpad-water based carpet system only due to an inconsistent bounce produced by the in-fill of the 3rd generation carpet. Player interaction tests were measured using the industry standard Berlin Artificial Athlete and the alternative 2.25 kg Clegg Hammer. The AAB provided measurements of force reduction, whereby increasing values indicated decreasing values of peak impact force. The Clegg Hammer provided measurements in peak deceleration, inverse to the AAB, whereby decreasing values indicated a reduction in peak impact force. The measurements of both devices, although different, relate the relationship between the reduction in peak impact force and increase in shock absorbency. Player interaction tests were conducted on shockpads and both shockpad-carpet systems. Durability was measured by the industry standard tensile test and the alternative cyclic fatigue test. The tensile test provided a measurement of tensile strength and the cyclic fatigue test a measure of durability through changes in player and ball interaction measurements and mass loss of the shockpad. Tensile tests were conducted on all shockpads and the cyclic fatigue test is in the preliminary stages of development and required and was therefore only conducted on shockpads with variations in binder content and thickness.

The results of mechanical testing are provided in graphical format. The same scale is used for each test method to demonstrate which variables have the largest effect on the mechanical behaviour of shockpad. The effect of each variable is discussed individually in terms of player and ball interaction behaviour and durability. Key variables for each mechanical property with and without carpet are identified and summarised in Table 4.12.

4.3.1 Binder Content

Three cast in-situ shockpads were constructed using binder contents of 5, 12 and 15%. When combined with the benchmark shockpad with a binder content of 9%, the effect of binder content on the mechanical properties of shockpads and shockpad-water based carpet system could be observed over the range of 5 to 15%.

The effect of binder content on vertical ball rebound resilience is shown in Figure 4.12. Rebound resilience of 36% was measured for all shockpads and was therefore not affected by the binder content over the range examined. The use of the water based carpet above the shockpad layers reduced ball rebound resilience to 30%. Therefore, the vertical rebound resilience of whole pitch construction was not influenced by the binder content of shockpads. Standard deviations are shown by the error bars in Figure 4.12 for both the shockpad and shockpad-water based carpet system. The small error bars can barely be seen vertically both sides of the marker and are consistent in size; showing good repeatability and small differences between measurements for each drop.

Player interactions were measured by Berlin Artificial Athlete and Clegg Hammer impacts. The effect of variations in binder content for AAB and Clegg Hammer tests for shockpads and shockpad-carpets systems are given in Figure 4.13 and Figure 4.14 respectively. The AAB tests show force reduction values to be 42% and peak deceleration measured by the Clegg Hammer to vary between 227 and 257 g's. Both player interaction tests show a constant relationship between player interactions and binder content over the range of 5 to 15%.

The same constant relationship between player interactions and binder content were observed for the shockpad-carpet systems as for the shockpad alone, however, shock absorbency is increased and peak deceleration decreased by the addition of carpet layers. Force reduction increased to 60% for the water based carpet system and between 57.5 and 60% for the 3rd generation carpet system. Peak deceleration reduced to average values of 115 g's for the water based carpet system and 107 g's for the 3rd generation carpet. AAB and Clegg Hammer measurements for the two different carpet systems showed similar results, however the 3rd generation showed a larger range in measurements due to the variability produced by the rubber and sand in-fill.

The similarity between the measurements for the two different carpets was surprising. It was anticipated the 3rd generation carpet would produce higher force reduction and lower peak decelerations than the water based carpet due to the 40 mm thick in-fill within the carpet fibres. However, these results demonstrate the effect of in-fill compaction, which was produced by rolling the carpet by the method described in Section 4.2.8.2, which produced mechanical properties similar to the water based carpet with a 3 mm integral shockpad.

The durability of shockpads with varying binder content was measured through tensile and cyclic fatigue tests. Results of tensile tests, Figure 4.15, showed tensile strength to vary from 21 to 71 kPa over the range of 5 to 15% binder content, which showed the largest effect of the mix design variables examined as part of this investigation. The increase in tensile strength achieved by increasing binder contents did not show a peak over the range examined and it is therefore anticipated tensile strength could be increased further with higher binder contents. The large error bars for each data point demonstrates the method is not repeatable and does not provide confidence in determining the effect of binder content on shockpad durability. Small voids or sections which contained relatively larger rubber particles were observed to produce origins of failure. However, as shockpads are not homogeneous materials, these issues were difficult to avoid.

Cyclic fatigue measurements were conducted on the benchmark shockpad (9% binder content) and the 5 and 15% binder content shockpads at this preliminary stage in the development of the test method. The results of cyclic fatigue testing are presented according to the two methods of shockpad failure; excessive changes in mechanical properties and loss of rubber particulate through rubber and binder bond breakdown.

Changes in mechanical properties for player interactions were measured using the Clegg Hammer and changes in ball interactions measured using the vertical ball rebound test. Peak deceleration measurements recorded using the Clegg Hammer, given in Figure 4.16, show all shockpads to increase with simulated mechanical degradation. The shockpad with 5 % binder content demonstrates the highest change in peak deceleration with an increase of 32 g's, while shockpads with 9 and 15% binder content increase by 21.5 g's. The increase in peak deceleration is attributed to the permanent reduction in thickness that occurs with increasing degradation as the Clegg Hammer results follow the same initial rapid increase which begins to plateau after 5 years. Thickness changes for all shockpads are 5.8%, which doesn't account for the higher peak decelerations recorded for the shockpad with 5% binder content. The additional peak deceleration change may be explained by the additional breakdown of the rubber to binder bonds of the 5% binder content shockpad which may reduce shock attenuation during impacts which is demonstrated by rubber mass loss. The effect of thickness change and breakdown of the rubber to binder bonds did not affect the hockey ball rebound resilience, shown in Figure 4.17, which remained constant at 36% for all shockpads.

The effect of shockpad thickness on failure through loss of rubber to binder bonds was measured by the reduction in shockpad mass. The relationship between mass loss and number of degradation cycles is given in Figure 4.18 for shockpads with binder contents of 5, 9 and 15%. The shockpad containing 5% binder content was shown to have the highest mass loss at 1.4%, with the 9 and 15% binder contents less at 0.9 and 0.5% respectively. These results show a trend of increasing mass loss with decreasing binder content suggesting that shockpads with lower binder content are more susceptible to failure by breakdown of the rubber to binder bonds than higher binder content shockpads.

Cyclic fatigue tests demonstrated low binder content shockpads are susceptible to failure by both mechanical property change and loss of rubber to binder bonds and therefore will show higher levels of degradation compared to higher binder content shockpads. Tensile test results indicate the effect of binder content on the strength of the rubber to binder bonds, however do not show how this will change with time or demonstrate the effect of mechanical property changes.

4.3.2 Bulk Density

The benchmark shockpad was constructed with a bulk density of 550 kg/m^3. Two further shockpads with densities of 500 and 600 kg/m^3 were constructed to quantify the effect of under and over compaction respectively. The results of mechanical test measurements for these two shockpads were combined with results for the benchmark shockpad to demonstrate the effect of bulk density variations in shockpads over the range of 500 to 600 kg/m^3.

The effect of bulk density on the vertical ball rebound resilience for shockpads and the shockpad-water based carpet system is shown in Figure 4.19. A constant rebound resilience of 36.5% was measured all three shockpads, which reduced to 30.5% by the addition of the carpet layer. These results indicate ball interactions are not influenced by shockpad bulk density over the range examined. The small error bars indicate good repeatability of the method.

Player interactions were measured using the Berlin Artificial Athlete and Clegg Hammer and the effect of bulk density is shown in Figure 4.20 and Figure 4.21 for the two tests respectively. AAB measurements show an increase in force reduction from 40.5 to 41.5% which is not considered significant, however peak deceleration measured by the Clegg Hammer reduces from 290 to 246 g's as bulk density is increased from 500 to 600 kg/m^3.

The increased sensitivity of the Clegg Hammer test to detecting changes in bulk density is explained in terms of the peak impact forces produced by each test. Peak impact force for the AAB test is calculated to be 4000 N by inputting a force reduction of 40% and peak impact force on a rigid surface of 6600 N into Equation 4.8. Peak impact forces for the Clegg Hammer test, calculated using the product of mass of the impact hammer and peak deceleration, ranged from 6400 to 5447 N. Peak impact forces produced by the Clegg Hammer were significantly higher than the AAB. Higher impact forces produce greater deformation of the shockpad and therefore obtain more interaction from the bulk of the shockpad. It is anticipated that by increasing bulk density, the denser rubber network was able to attenuate the impact within the shockpad itself with minimal force transference to the rigid foundation layer below and therefore provide higher levels of shock absorbance. The initially rapid increase in shock absorbance appears to plateau, indicating 600 kg/m^3 further increases in bulk density above 600 kg/m^3 may not continue to produce further increases in shock absorbency. The standard deviation for this shockpad, however, makes it difficult to confidently predict if the plateau has been reached or if shock absorbency continues to increase with increasing bulk density.

The addition of the water based and 3rd generation carpet layers eliminated the effect of bulk density that was observed for the shockpad layer alone. AAB measurements showed constant force reduction of 60 and 57% for the water based and 3rd generation carpet systems respectively. Clegg Hammer measurements provided peak decelerations of 117 and 107 g's for the water based and 3rd generation carpet systems respectively. The effect of bulk density on player interactions is not observed for shockpad-carpet systems as the carpet layer reduces the force transferred to the shockpad. Calculations of peak impact force for Clegg Hammer impacts show it is reduced to 2500 N by addition of the carpet layer. The magnitude of peak impact force is similar the AAB peak impact forces calculated for the shockpad alone where no effect of bulk density was observed.

The durability of shockpads measured through tensile measurements is given in Figure 4.22. Tensile strength was shown to increase with increasing bulk density over the range of 27 to 50 kPa for shockpads with a bulk density of 500 to 600 kg/m^3. The large standard deviations, particularly the 600 kg/m^3 shockpad, demonstrate the method was not repeatable and produces difficultly in ascertaining the relationship between bulk density and tensile strength. However, the increasing tensile strength with bulk density was expected as the denser packing of rubber particles produces a higher number of contact points between rubber particles that must be broken to produce failure. The increased rubber contact produced in higher density shockpads is also anticipated to demonstrate increased durability through cyclic fatigue measurements.

4.3.3 Thickness

The benchmark shockpad was constructed with a thickness of 12 mm to replicate those commonly constructed for water based hockey pitches. The mechanical property effect of constructing shockpads below this specified thickness was examined through the construction and testing of an 8 mm shockpad. Also, the variability in player and ball interactions and durability produced by the construction of 15 and 20 mm shockpads commonly used in football and rugby pitches was also examined. Overall, the effect on mechanical properties of varying shockpad thickness over the range of 8 to 20 mm was examined as part of this investigation.

The effect of shockpad thickness on ball interactions was measured using a vertical hockey ball rebound test. The effect of shockpad thickness on rebound resilience is shown in Figure 4.23. A constant relationship between thickness and rebound resilience of 36.5% was measured for shockpads of 12 mm thickness and above. The 8 mm shockpad shows a reduction in ball rebound resilience at 32% therefore producing a lower ball rebound height. The addition of the water based carpet eliminates the reduced rebound resilience for the 8 mm shockpad by producing a constant ball rebound resilience of 30% for all shockpads.

The effect of shockpad thickness on player interactions was measured using the Berlin Artificial Athlete and Clegg Hammer. Force reduction measured by the AAB,

Figure 4.24, increases with increasing shockpad thickness from 31 to 56% over the thickness range of 8 to 20 mm. A similar trend was shown for the Clegg Hammer impacts in Figure 4.25, where peak deceleration decreased with increasing shockpad thickness from 444 to 122 g's over the range of shockpad thicknesses. The reading of 444 g's output by the Clegg Hammer indicates the upper limit of measurement for the device and therefore peak deceleration measurements on the 8 mm shockpad may be higher but were unable to be measured. Both tests show a similar relationship between shockpad thickness and shock absorption with an initially rapid change from 8 to 15 mm thickness which begins to plateau for shockpads above 15 mm in thickness.

The effect of shockpad thickness on player interactions is explained by the varying stiffness levels reached and the subsequent influence from the rigid foundation layer below. The non-linear behaviour of shockpads published by Walker (1996) shows an initially low stiffness which transitions to a higher stiffness. Thinner shockpads reach a higher stiffness through player impact than thicker shockpads and therefore transfer more force to the rigid foundation layer below. Thicker shockpads, such as 15 and 20 mm, are able to maintain a lower stiffness as there is more allowance for deformation and therefore produce less force transfer to the foundation layer. The combined behaviour of a stiff shockpad and rigid foundation layer for thinner shockpads produce low shock absorbance.

The addition of the carpet layer reduced the effect of shockpad thickness on player interactions; however an effect was still measured. Force reduction measurements on for the water based carpet system increased to 56 to 65% and 54 to 63% for the 3rd generation carpet system over the 8 to 20 mm range in shockpad thickness. Peak deceleration measurements were similar for the water based and 3rd generation carpets ranging from 128 to 83 g's. It was observed measurements for both the AAB and Clegg Hammer tests showed a more linear relationship to shockpad thickness for the carpet systems where a polynomial or exponential relationship was observed for the shockpad layer alone.

Shockpad thickness was shown to be a key variable for both ball and player interactions. The results for both player and ball interactions compare well with those published by Young (2006). Calculation of rebound resilience from the published results provides a range of 30.5 to 36% for shockpads of 9 to 20 mm thickness, which show a similar range the results of this investigation. Player interactions measured by the AAB and Clegg Hammer show a similar range but shifted to higher shock absorptions for each thickness and the use of a non-linear scale by Young (2006) prevents the shape of the relationship from being compared. The differences in between the two sets of measurements can be explained by the testing of a combination of newly constructed and worn shockpads from site by Young (2006). Mix design variables other than thickness were not controlled for shockpads and therefore may have influenced results. However, findings from both studies indicate that the rapid changes in player interaction properties that occur for shockpads ranging from 8 and 15 mm in thickness require strict control of thickness and additional verification procedures should be implemented by sporting governing bodies to ensure specifications are met.

The durability of shockpads for varying layer thickness was measured through tensile strength and cyclic fatigue measurements. Tensile strength was shown to increase with shockpad thickness in Figure 4.26 from 21 to 56.5 kPa over the range of 8 to 20 mm thickness. The effect of thickness on tensile strength is explained by the higher number of rubber to rubber contact points achieved in a thicker shockpad. The 8 mm shockpad could be only one particle thick in places due to the 2 – 6 mm rubber size used and will therefore proportionally have less rubber contact points. In addition, the increased number of contact points between particles reduces the susceptibility of premature failure due to rubber packing imperfections which is reflected in the reducing standard deviations as shockpad thickness increased.

Through cyclic fatigue testing, shockpad thickness was shown to produce variation in the extent of mechanical degradation in shockpads. Preliminary testing was limited to the benchmark shockpad and the 8 and 20 mm shockpads at either end of the range of shockpads tested to provide an initial assessment of the test method and examination of the results it was able to provide. The effect of shockpad thickness on mechanical degradation was assessed in terms of the two failure modes of shockpads; excessive changes in mechanical properties and loss of rubber to polyurethane bonds.

Changes in mechanical properties for player interactions were measured using the Clegg Hammer. Peak deceleration values were only able to be recorded for the benchmark (12 mm) and 20 mm shockpad as peak deceleration values for the 8 mm shockpads were above the Clegg Hammer limit. A increase in peak deceleration values were measured for the 12 and 20 mm shockpad, with the 20 mm shockpad showing the largest increase of 25 g's, shown in Figure 4.27. This reduction in peak deceleration results in reduced shock absorbency for the shockpad and is attributed to the permanent reduction in thickness. The largest changes in thickness was observed by the 20 mm shockpad at 7.3% and peak deceleration measurements also demonstrate the same trend as changes in thickness which show rapid change for the first five years and then reach a plateau. This reduction in thickness is explained by the permanent compaction of air voids. However, the change in thickness was not significant enough to affect ball rebound resilience as shown in Figure 4.28. Constant relationships between ball rebound resilience and number of degradation cycles are shown for the 8, 12 and 20 mm shockpads.

The effect of shockpad thickness on failure through loss of rubber to binder bonds was measured by the reduction in shockpad mass. The relationship between mass loss and number of degradation cycles, given in Figure 4.29 for 8, 12 and 20 mm shockpads, shows the 8 mm shockpad to have the highest mass loss at 2.6% with significantly less for the 12 and 20 mm shockpad at 0.8 and 0.4% respectively. The increased mass loss of the 8 mm shockpad is attributed less rubber to rubber contact points as may be, in places, only one particle thick.

Cyclic fatigue testing showed shockpad thickness to affect degradation through both change in mechanical properties and mass loss of the rubber. Thicker shockpads were shown to be more susceptible to degradation through changes in player interactions and thinner shockpads were shown to be more susceptible to loss of bonds between the rubber and binder. Tensile tests were able to indicate the effect of shockpad thickness on mass loss through breakdown of the rubber bonds but were not able to quantify the extent of this loss over time and also lacked the ability to demonstrate the 20 mm shockpad could fail due to changes in player interactions.

4.3.4 Particle Size and Distribution

Rubber particulate in size ranges of 2 to 6 mm and 2 to 8 mm were compared for a predominantly small sized distribution (1), a well-graded distribution (2) and a predominantly large sized distribution (3). The benchmark shockpad contained a well-graded rubber distribution in the 2-6 mm rubber size. A further five shockpads were constructed to examine the effects of particle size and particle size distribution on shockpad mechanical properties.

The effect of rubber size and distribution on ball interactions is shown in Figure 4.30. The vertical ball rebound resilience shows a constant relationship between rubber size and distribution with an average value of 36%. The addition of the water based carpet layer reduces rebound resilience but retains a constant relationship with rubber size and distribution with an average of 30.5%. These results show there is no effect from rubber size and distribution over the range examined for shockpads and shockpad-carpet systems.

Player interactions were measured through AAB and Clegg Hammer Impacts and are shown in Figure 4.31 and Figure 4.32 respectively. Force reduction measurements taken using the AAB show similar results for the 2 to 6 mm rubber size distributions with small-sized and well-graded distributions recording 41% force reduction and slightly increased for the larger sized distribution at 42.5%. Increased variation was shown by the 2 to 8 mm sized distributions which ranged from 38 to 44% and demonstrated higher shock absorbency for small and large sized distributions. Clegg Hammer results did not show the same trend for the 2 to 6 mm sized distributions. The well-graded distribution shows a raised peak deceleration of 257 g's compared to 229 and 225 g's for the small and large size distributions. The trend for the 2-8 mm sized distributions using the AAB were replicated for the Clegg Hammer results with the small-sized distribution recording the lowest peak deceleration and the well-graded distribution recording the highest. Overall, Clegg Hammer measurements showed a similar trend for 2-6 and 2-8 mm distributions with the well-graded distributions showing the highest peak deceleration and therefore the lowest shock absorbency when compared to the small and large-sized distributions. The effect of rubber size and distribution is attributed to the different air void configuration and number of contact points between rubber particles that are achievable. No studies could be found in the literature could be found that examine air voids configurations or the interactions between bound rubber particles within a shockpad structure that would assist providing a detailed explanation of the rubber size effect on player interactions. However, it is anticipated that a compromise exists between larger rubber sizes producing larger air voids that are able to deform easily under impact and small rubber particles that share more rubber to rubber contact points that are able to dissipate the shock of an impact more effectively. This comprise explains the reduced shock absorbency of the well-graded structure than contains a mix of small, medium and large sized rubber particles.

The addition of carpet layers produced a constant relationship between rubber size and distribution and mechanical properties related to player interactions. Some effect of the small-sized distribution for the 2-8 mm rubber size was observed for AAB and Clegg Hammer tests showing an increased level of shock absorbency of 2% force reduction and 10 g's compared to well-graded and large sized distributions. Overall, an effect of rubber size and distribution on player interactions were measured, however, by the addition of a carpet layer the effect is reduced and is not considered large enough to be detected by players.

The tensile strength of shockpads with varying rubber size and distribution is shown in Figure 4.33. Tensile strength of the 2 to 6 mm rubber sized distributions is shown to be higher for the small-sized distribution at 39 kPa and constant for the well-graded and larger sizes at 34 kPa. For the 2 to 8 mm rubber sizes, tensile strength is constant for the small-sized and well-graded distributions at 40 kPa and increases to 54.5 kPa for the large-sized distribution. The 2 to 8 mm rubber sizes produce higher tensile strength than the 2 to 6 mm rubber sizes for each distribution, however the large standard deviations show results for the two rubber sizes may overlap. The increased tensile strength for the 2 to 8 mm rubber size is explained by the decreased surface area of the larger sized particles compared to the 2 to 6 mm rubber size. The reduced surface area provides a thicker coating of binder and therefore more binder is available at rubber to rubber contact points where shockpad strength is achieved. This also accounts for the increasing tensile strength with larger-sized distributions for the 2 to 8 mm rubber size. There may be a compromise of increased binder coverage with fewer rubber contact points for larger rubber sizes and for these reasons rubber size and distributions are also anticipated to effect durability measurements through cyclic fatigue testing.

4.3.5 Binder Type

The benchmark shockpad used polyurethane binder from one manufacturer that was recommended for shockpads produced in the UK. In addition, shockpads were constructed using polyurethane binders from a further two manufacturers with the same recommendations. Therefore, the variations in shockpad mechanical properties produced by three different binders were able to be measured and compared.

The effect of binder type on ball interactions is shown in Figure 4.34. Rebound resilience is similar for all three binders, with Binder 1 showing a slightly increased rebound resilience of 36.5% compared to 35.5% for Binders 2 and 3; however this increase is not considered significant as this equates to a 1.5 cm rebound height increase. The addition of the water-based carpet layer negates the effect of binder type providing a constant reduced rebound resilience of 30% for all binder types.

The effect of binder type on player interactions for shockpads and shockpad-carpet systems was measured by the Berlin Artificial Athlete and Clegg Hammer and is given by Figure 4.35 and Figure 4.36 respectively. Force reduction values for AAB impacts are the same for Binders 1 and 2 at 41% and a slight increase for Binder 3 at 43%. The Clegg Hammer demonstrates a similar trend of similar measurements of peak deceleration for Binders 1 and 2 at 257 and 251 g's and a reduction for Binder 3 at 241 g's. This suggests the mechanical properties of Binder 3 may be different to those of Binders 1 and 2, perhaps possessing a lower stiffness that allows more movement of the rubber to attenuate shock from the impact. However, these changes measured in player interaction due to binder content are not considered large enough to be detected by players using the pitch, particularly when the addition of the water based and 3rd generation carpets negates the effect of binder type. Force reduction is increased to 60 % and 57 % and peak deceleration decreased to an average of 100 and 105 g's for the water based and 3rd generation carpet systems respectively. The reduced effect of binder type by the addition of the carpet layers is explained by the reduced force transferred to the shockpad by the carpet layers.

The effect of binder type on shockpad durability indicated by tensile strength is shown in Figure 4.37. Tensile strength ranged from 34 to 44 kPa for the three different binders. The large standard deviations for all binder types, particularly Binder 2, show repeatable measurements of tensile strength were not able to be obtained and the effect of binder type not able to be accurately compared. It is anticipated binder type may produce different values of durability using cyclic fatigue measurements as it was suggested the different binders may possess different mechanical properties from the results of player interaction tests.

4.4 Discussion

The investigation into the effect of mix design variables on shockpad mechanical properties has shown that binder content, thickness, rubber particle size and distribution, bulk density and binder type all have some effect on mechanical properties. This section provides a discussion of mechanical properties in terms of ball interactions, player interactions and durability and identifies key variables for each mechanical property. The industry standard mechanical property tests are compared to alternative tests trialled as part of this investigation and an assessment of the suitability of the alternative tests is provided. This discussion forms the basis for a set of recommendations to the sports surfacing construction industry and sporting governing bodies regarding key variables that need to be closely controlled during shockpad construction, verification that mix design specifications have been met and identifies new methods for shockpad mechanical property testing.

Player and Ball Interactions

Player interactions were measured using Berlin Artificial Athlete and 2.25 kg Clegg Hammer. The results of both tests showed the same trends in identifying thickness, rubber size and size distribution, binder type and bulk density as mix design variables affecting player interactions. The vertical hockey ball rebound test demonstrated ball interactions were only affected by shockpad thickness.

The results of testing highlighted the similarities between the player and ball interaction test methods, which assists in providing a better understanding of how mix design affect both aspects of shockpad mechanical properties. Both tests, in principle, involved the impact of the shockpad with a mass and measured the mechanical response of the shockpad. However, the energy input by the mass during impact differs for the two tests and therefore the material response. The ball interaction test involves a mass of 160 grams impacting the shockpad from a height of 1.5m, providing an input energy of 2.35 J. The Clegg Hammer involves a 2.25 kg mass impacting the shockpad from a height of 0.45 m, providing an input energy of 9.93 J. The potential (input) energy of the Berlin Artificial Athlete is difficult to measure due to the rubber dampers used to attenuate the falling mass prior to impact but was identified by Fleming et al (2004) as being similar to the Clegg Hammer. The energy input during player interaction tests is over 4 times that of the ball interaction tests and therefore involves more interaction with the bulk of the shockpad. This difference in the extent of interaction explains why player interactions are affected by bulk properties of the shockpad such as rubber size and distribution, bulk density and binder type. Thickness is the only mix design variable common to both player and ball interaction tests as the ball interaction test inputs enough energy to produce significant interactions within the shockpad at 8 mm thickness.

The introduction of the new carpet layer eliminated the effect of shockpad thickness for ball interactions and bulk density, binder type and rubber size and distribution for player interactions. The effect of thickness was reduced for player interactions, but differences in mechanical properties were still measurable. The role of the carpet in eliminating the effect of bulk density, binder type and rubber size and distribution from player interactions and thickness for ball interactions is explained by the reduction in energy (and force) transferred to the shockpad. Energy input into shockpad-carpet system is first used in deforming the carpet pile, in-fill materials and integral shockpads and therefore reduces the amount transferred to deform the shockpad. Mix design variables, such as bulk density, binder type and rubber size and distribution are considered secondary variables as their effects were not measured through the carpet layer, however the effect of carpet wear requires consideration. The water based and 3rd generation carpets used in this investigation were new and the effect of carpet wear and in-fill compaction. In-service carpets wear and in-fill compacts and therefore it is anticipated increased levels of energy will be transferred to the shockpad with time. Player and ball interaction characteristics are thought to shift towards the mechanical properties for the shockpad layer alone and therefore secondary variables may also begin to affect the properties of the whole pitch.

Durability

Durability measures time required to produce shockpad failure. Mechanical degradation was shown in the literature review to produce shockpad failure by two mechanisms; excessive changes in mechanical properties and breakdown of bonds between the rubber and binder to produce loose rubber particulate. Durability was measured by the current standard method of tensile testing, however, criticisms regarding the usefulness of the test in simulating the mechanisms of shockpad failure led to the development of a cyclic fatigue test. Tensile testing was conducted on each shockpad constructed for this investigation combined with preliminary cyclic fatigue tests on shockpads with binder content and thickness variations.

Tensile measurements showed all mix design variables to affect durability, particularly binder content. The analysis of tensile test results showed they were influenced by the number of contact points between rubber particles and the quantity of binder available to produce bonds between rubber particles. Increases in bulk density and thickness increased the number of contact points between rubber particles, increases in binder content increased the quantity of binder available for bonding, rubber particle size and distribution produced a compromise between rubber contact points and binder availability and binder type influenced binder properties and the bond strength between and rubber and binder.

Preliminary cyclic fatigue measurements for binder content and shockpad thickness showed both variables to affect shockpad durability. As the test method is at the preliminary stages of development, upper limits for changes in player and ball interactions and loss of rubber particulate to indicate failure were not able to be established to quantify the effect of thickness and binder content on service life of shockpads. However, the results do indicate that both changes in thickness and binder content influence shockpad durability and all other mix design variables are also expected to influence shockpad durability.

Recommendations

The results of player and ball interaction and durability tests showed shockpad thickness, bulk density, binder content, binder type and rubber size and size distribution to affect the functional mechanical properties of shockpads. It is therefore recommended that appropriate values for these mix design variables be specified and strict limits of acceptable variance be placed on each variable by sporting governing bodies to ensure consistent playing performance and sufficient in-service life of the synthetic pitch system.

Further to these recommendations, mix design and mechanical property verification tests should be specified by sporting governing bodies to ensure correct construction procedures are followed and specifications are met. The standard vertical ball rebound test used for whole pitch constructions is recommended to detect changes in ball rebound properties. In addition to the ball interaction test, the development and evaluation of alternative mechanical test methods to those currently used as standard within the industry has yielded promising results for the development of shockpad specific tests.

A player interaction test of the shockpad layer in-situ is required to be introduced as variations in thickness, bulk density, binder type and rubber size and distribution were shown to affect mechanical properties. Testing conducted with and without carpet layers showed shockpad thickness to be a key mix design variable. A marked reduction was measured for other mix design variations being identified by player interaction tests with the carpet layer, however, the effect of carpet wear and in-fill compaction will result in increased energy transfer to the shockpad and the effect of mix design variations may become more pronounced over the service life of the pitch.

Alternative Test Method Development

The Berlin Artificial Athlete (AAB) test is stipulated by the FIH, FIFA and the IRB as the method to measure player interaction properties for whole pitch constructions.

However, the AAB is an expensive and specialised piece of equipment, requiring testing to be carried out by a test house. It is also heavy and cumbersome which limits the number of test positions that can be examined. The 2.25 kg Clegg Hammer was developed for use on synthetic sports pitches by Young (2006) as a more portable alternative to the AAB.

This investigation has shown the Clegg Hammer to have merit as a player interaction test. It offers a simple, portable and inexpensive test that is capable of detecting variations in the mix design of shockpads. The test was shown to detect changes in the thickness, bulk density, binder type, and rubber size and distribution of shockpads, highlighting areas of the pitch where mix design may vary from specification. Conducting Clegg Hammer impacts on the shockpad layer in-situ prior to carpet installation allows these variations in mix design to be identified and rectified. Mechanical property changes due to mix design were shown to be reduced by addition of the carpet and so may not be detected in initial testing, only becoming apparent once the carpet layer begins to wear and in-fill materials compact.

Shockpad durability is currently assessed within the sports surface construction industry using measurements of shockpad tensile strength. The test is specified to determine sufficient binder content in the cured shockpad which is linked to shockpad durability by anecdotal evidence. Tensile test results from this investigation showed binder content to have a significant effect of tensile strength; however, all other mix design variables also affected tensile strength. The tensile test is therefore not a reliable indicator of binder content. In addition, the test was shown to be limited in its ability to accurately measure durability in three crucial aspects; accurate simulation of the mechanisms of in-service shockpad degradation, providing a relationship between tensile strength and time-to-failure and inability to detect failure through excessive mechanical property changes. Test results consistently produced large standard deviations that demonstrated the method was not repeatable due to its sensitivity to voids and rubber packing imperfections, which subsequently prevented confident assessment of the effect of mix design variables on shockpad durability.

The cyclic fatigue test addressed the limitations of the tensile test by simulating degradation from player interactions, where number of cycles could be related to the age of the shockpad in years, and providing measurements of both methods of shockpad failure. Currently, the method is at the preliminary stages of development and requires limits to be set on mechanical property changes and rubber loss to quantify failure and also further testing to determine the repeatability of measurements. However, at this stage it offers a potential alternative test method to the tensile test to better investigate mechanical property changes over time.

4.5 Summary

An investigation into the effect of mix design variables has provided the identification of thickness as a key mix design variable in player and ball interactions, with bulk density, binder type and rubber size and size distribution as secondary variables affecting player interactions. All of the mix design variables examined as part of this investigation were shown to influence durability.

The findings of this testing programme have formed several recommendations to the sports surface construction industry and sporting governing bodies. Firstly, all mix design variables identified as part of this investigation (thickness, binder content, bulk density, binder type and rubber size and size distribution) should be specified and strict limits of acceptable variation placed on each variable by sporting governing bodies to ensure consistent playing performance and sufficient in-service life of the synthetic pitch system. Secondly, mix design and mechanical property verification tests should be specified by sporting governing bodies to be conducted on the in-situ shockpad to ensure correct construction procedures are followed and specifications are met.

Two alternative mechanical test methods developed as part of this investigation, show potential for incorporation into performance standards issues by sporting governing bodies. Preliminary cyclic fatigue test results demonstrated the method has potential to provide a performance related durability test for shockpads. The method offers a more accurate simulation of player impacts producing mechanical degradation in shockpads and allows failure to be identified by both excessive changes in mechanical properties and dissociation of the rubber particles from the matrix.

The 2.25 kg Clegg Hammer also showed merit as a simple, portable and inexpensive test that could be used to examine the response of the shockpad to player interaction prior to installation of the carpet layer. The hammer was capable of detecting changes in shockpad thickness, bulk density, rubber size and size distribution and binder type that may not be detected for new pitch constructions with current performance specifications, but may become apparent as the carpet ages. This test, able to be performed by the pitch constructor prior carpet installation, is recommended as a useful additional test to ensure the long term synthetic pitch mechanical properties remain within the required limits.

Constituent Material	Design Variables	Construction Variables
Rubber Type	Layer Thickness	Bulk Density
Rubber Size	Binder Content	Cure Temperature
Rubber Size Distribution		Cure Humidity
Rubber Shape		Mixing Time
Binder Type		

Table 4.1: Shockpad constituent materials, design and construction variables

Controlled and Varied	Controlled
Rubber Size	Rubber Type
Rubber Size Distribution	Rubber Shape
Binder Type	Cure Temperature
Binder Content	Cure Humidity
Layer Thickness	Mixing Time
Bulk Density	

Table 4.2: Mix design variables to be varied and controlled and those to be controlled and not able to be varied

Variable	Shockpad 1	Shockpad 2
Rubber Type	Truck tyre or SBR rubber	SBR rubber
Rubber Size [mm]	Not specified	2 – 6
Rubber Size Dist.	Not specified	Not Specified
Rubber Shape	Crumbed	Crumbed
Binder Type	Polyurethane	Polyurethane
Binder Content [%]	> 8	9
Layer Thickness [mm]	12±2mm	12
Bulk Density [kg/m^3]	As per reference sample	-

Table 4.3: Specifications of site-laid shockpads

Property	Site 1	Site 2
Thickness [mm]	13.66 (3.1)	12.95 (2.1)
Bulk Density [kg/m^3]	551.8 (13.2)	568.1 (10.2)

Table 4.4: Thickness and bulk density of site-laid cast in-situ shockpads (Standard deviations from 5 tests on 3 samples)

Variable	Standard Value	Acceptable Variation
Rubber Type	Recycled Rubber Particulate	N/A
Rubber Size	2 – 6mm	N/A
Rubber Size Distribution	Well Graded	N/A
Rubber Shape	Crumb	N/A
Binder Type	Moisture Cured Polyurethane	N/A
Binder Content	9%	N/A
Layer Thickness	12mm	±1mm
Bulk Density	550 kg/m^3	±30kg/m^3
Mixing Time	3 minutes	± 5 secs

Table 4.5: Design of industry standard shockpad

Mix Design Variable	Range Examined
Rubber Size [mm]	**2-6** 2-8
Rubber Size Distribution	Small **Well-Graded** Large
Binder Type	**1** 2 3
Binder Content [%]	5 **9** 12 15
Layer Thickness [mm]	8 **12** 15 20
Bulk Density [kg/m^3]	500 **550** 600

Table 4.6: Variable ranges examined. Note. Bold values represent industry standard shockpad

Sieve Mesh Size [mm]	Size Class [mm]
10.00	10 or greater
8.00	8.00 - 9.99
6.30	6.30 – 7.99
5.00	5.00 – 6.29
3.35	3.35 – 4.99
2.36	2.36 – 3.34
2.00	2.00 – 2.35
1.18	1.18 – 1.99
Pan	1.17 or less

Table 4.7: Sieve sizes, rubber size designation and their respective size classes

Mix Design Variable		Bulk Density [kg/m^3]	Thickness [mm]	Binder Content [%]
Benchmark	-	541.48 (8.5)	12.36 (0.4)	9.2
Binder Content	5%	546.43 (5.7)	12.21 (0.4)	5.2
	12%	548.52 (3.4)	12.23 (0.3)	11.8
	15%	543.56 (5.3)	12.19 (0.7)	14.6
Thickness	8 mm	547.78 (5.4)	8.32 (0.5)	8.1
	15 mm	541.90 (4.3)	15.12 (0.2)	8.3
	20 mm	548.34 (2.1)	20.04 (0.4)	8.7
Rubber Size & Distribution	2-6 Dist 1	543.54 (4.2)	12.29 (0.3)	8.6
	2 -6 Dist 3	539.78 (6.5)	12.54 (0.4)	9.1
	2-8 Dist 1	546.45 (5.4)	12.34 (0.3)	9.2
	2-8 Dist 2	549.65 (3.2)	12.24 (0.3)	8.7
	2-8 Dist 3	542.39 (4.7)	12.15 (0.6)	8.7
Bulk Density	500 kg/m^3	497.54 (5.9)	12.04 (0.3)	9.2
	600 kg/m^3	594. 32 (7.6)	12.13 (0.2)	8.9
Binder Type	2	546.34 (8.1)	12.44 (0.8)	8.6
	3	549.32 (6.3)	12.21 (0.4)	8.7

Table 4.8: Mix design verification results for shockpads of varying mix design. (Average and standard deviations for thickness and bulk density from 5 measurements)

Researcher	Movement	Vertical Force [BW]	Horizontal Force F-A [BW]	Horizontal Force M-L [BW]	Contact Time [sec]	Vertical Force [N]	Max Horizontal Force [N]	Resultant	Shear Angle	Freq [Hz]
Adrian and Xu (1990)	Walking	1.33	0.25	0.1	1.1	978	183	995	11	0.9
	Running	2.5	0.33	0.33	0.3	1839	242	1855	7	3.3
	Veering	2	0.33	0.83	0.3	1471	613	1594	22	3.3
	Cutting	2	0.67	0.67	0.65	1471	492	1551	18	1.5
	Stopping	2.67	0	0	0.5	1964	0	1964	-	2
	Dodging	2.67	0	0.67	0.9	1964	493	2025	14	1.1
	Pivoting	2.67	0.17	0.17	1	1964	122	1968	3	1
	Jumping	2	0.33	0.33	1	1471	242	1491	17	1
	Landing	3.33	1	0	0.5	2450	753	2558	16	2
	Lunging	2.67	0.75	0.13	1	1964	551	2040		1
Blackburn et al (2005)	Cutting	-	-	-	0.23	3250	2000	3816	31	4.3

Table 4.9: Vertical and horizontal forces for various sporting movements based on a 75 kg player. F-A and M-L designations for fore-aft and medial-lateral directions respectively.

Parameter	Specification
Resultant Force	1817 N
Vertical Force Component	1800 N
Horizontal Force Component	250 N
Frequency	2 Hz
One Year Equivalent	692 000 cycles

Table 4.10: Cyclic fatigue test specifications for accelerated aging of shockpads

Carpet Type	Generic Water Based	Generic 3rd Generation
Pile Height	12mm	65mm
Pile Weight	3.95 kg/m^3	1015g/m^2
Polymer Type	Nylon	Polyethylene
In-fill Materials	-	Rubber, Sand
In-fill Height	-	Sand: 15mm Rubber: 25mm
In-fill Weight	-	Sand: 16.5 kg/m^2 Rubber: 16.5 kg/m^2
Integral Shockpad	3mm foam	-
Suitable Sports	Hockey	Football, Rugby

Table 4.11: Specifications for generic water-based hockey carpet and 3rd generation carpet used for testing

	Player Interactions		Ball Interactions		Durability	
	Shockpad	Carpet	Shockpad	Carpet	Tensile	Cyclic Fatigue
Thickness	Y	Y	Y	×	Y	Y
Binder Content	×	×	×	×	Y	Y
Bulk Density	Y	×	×	×	Y	-
Rubber Size & Distribution	Y	×	×	×	Y	-
Binder Type	Y	×	×	×	Y	-

Table 4.12: Summary of the effect of each mix design variable on player interactions, ball interactions and durability for shockpads and shockpad-carpet systems

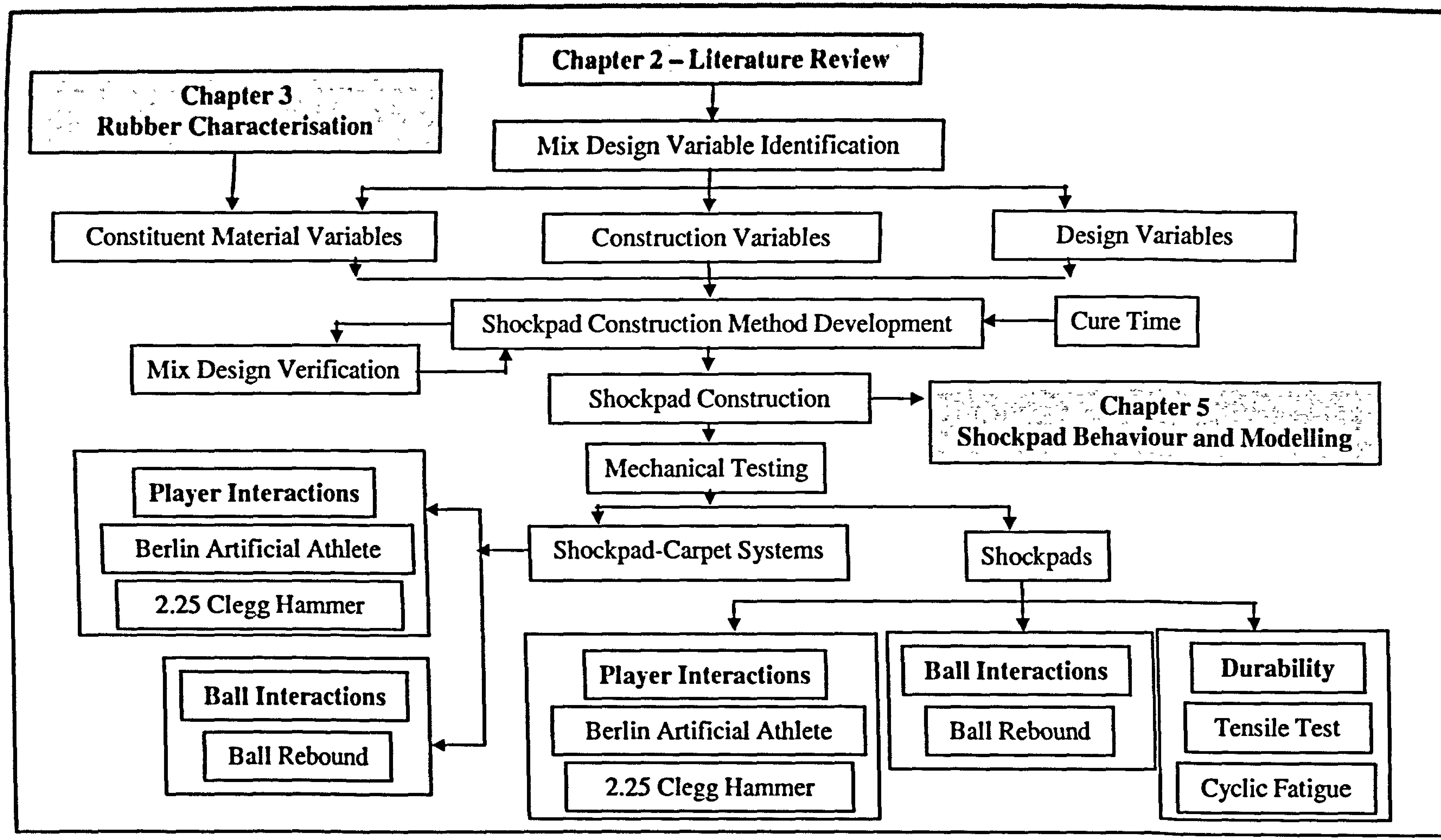


Figure 4.1: Flowchart of the process undertaken for mix design identification, shockpad construction and mechanical testing

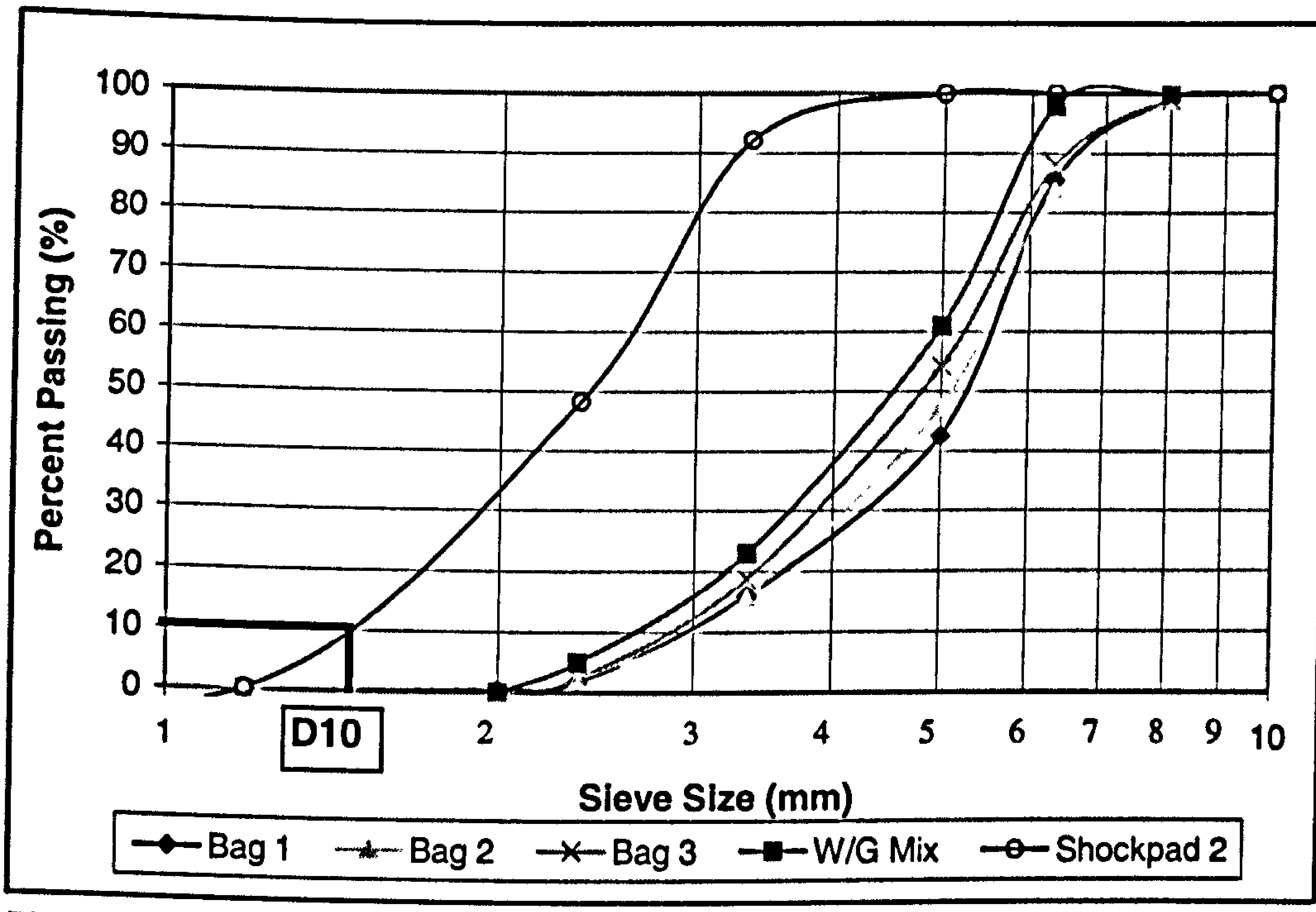


Figure 4.2: Comparison of a typical well-graded particle size distribution with bags supplied by a rubber recycler and recycled rubber particulate taken from the site of the second shockpad construction.

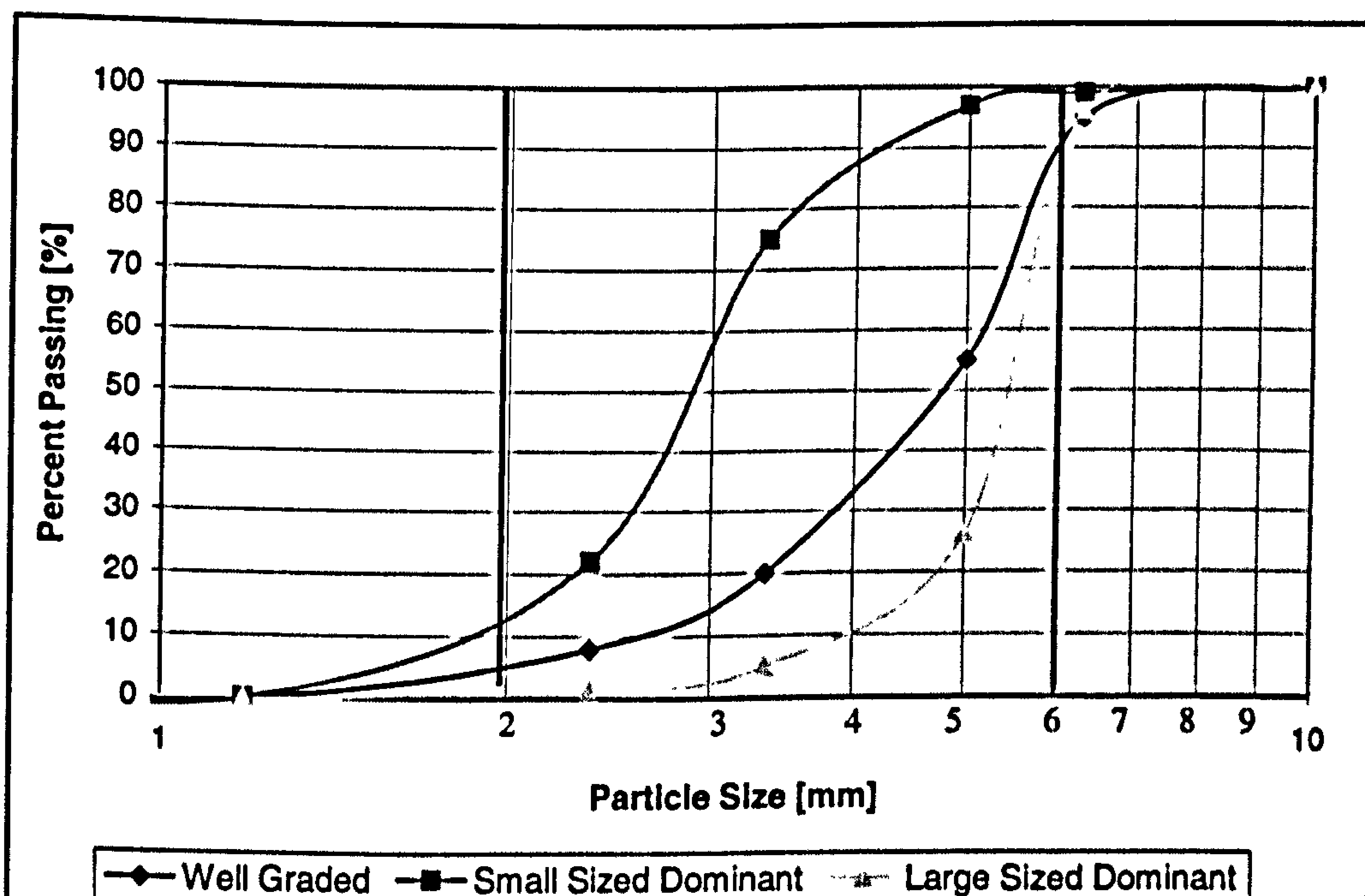


Figure 4.3: Standard, small size dominated and large size dominated particle size distributions.

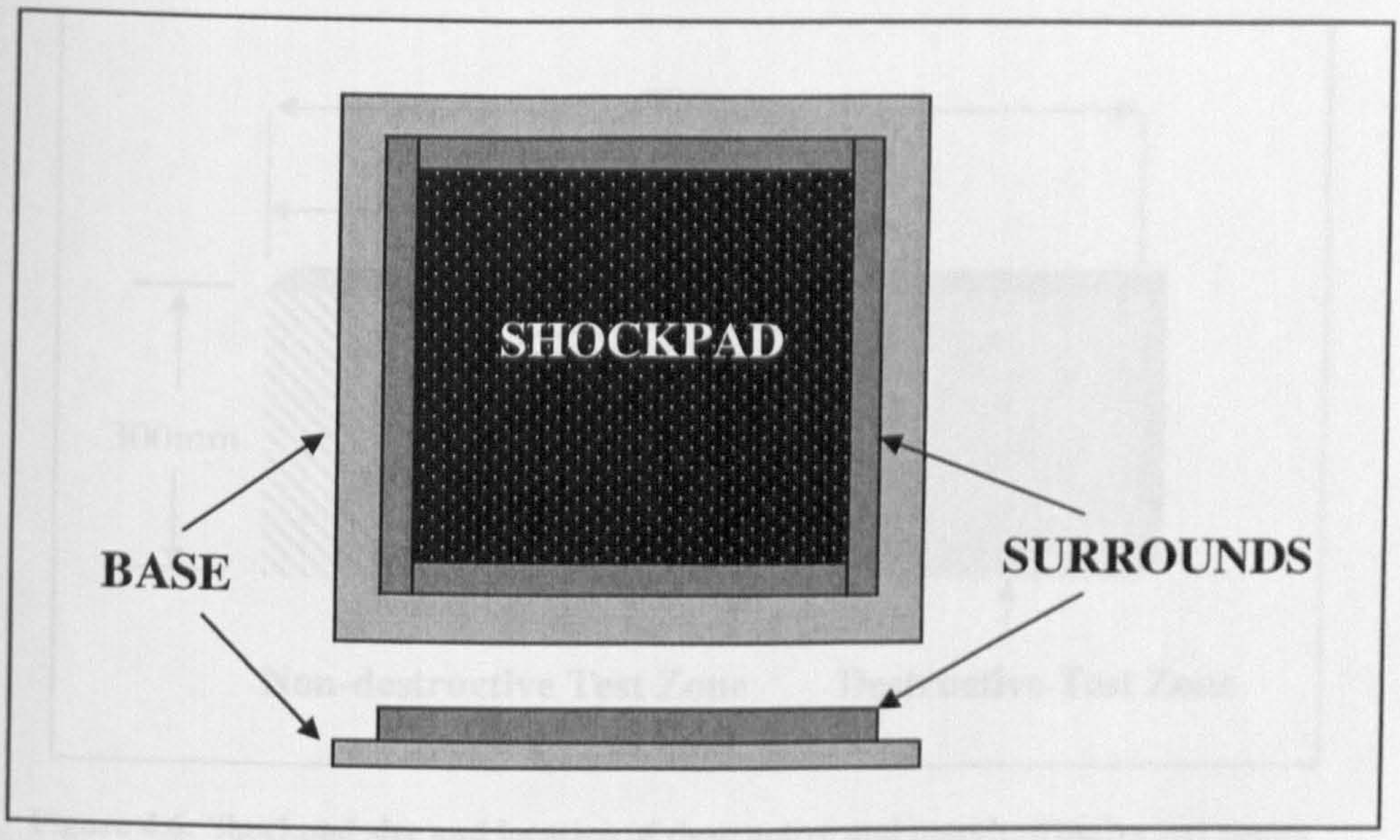


Figure 4.4: Wooden mould used for hand laying shockpads.

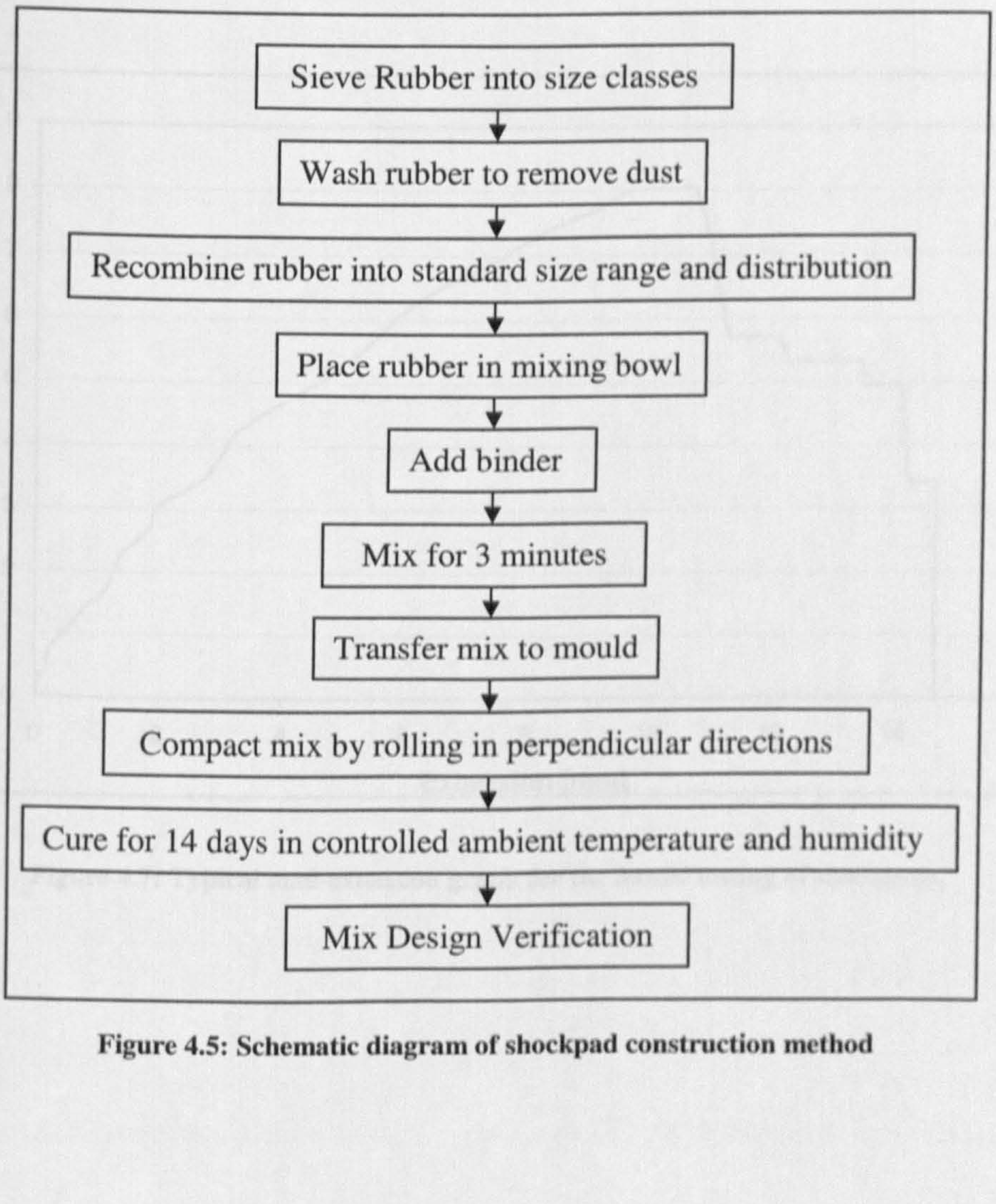


Figure 4.5: Schematic diagram of shockpad construction method

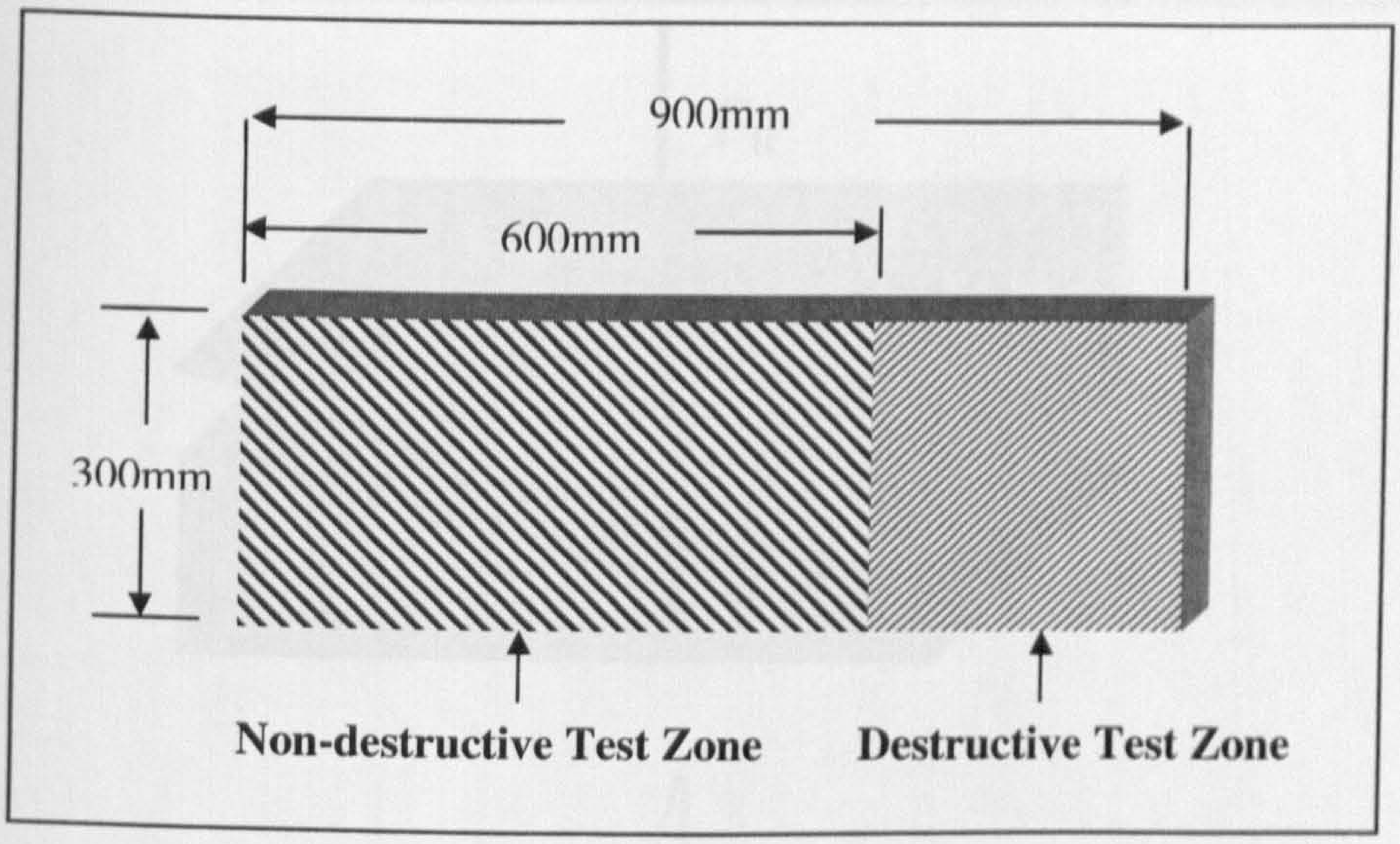


Figure 4.6: Shockpad size and location of destructive and non-destructive test zones.

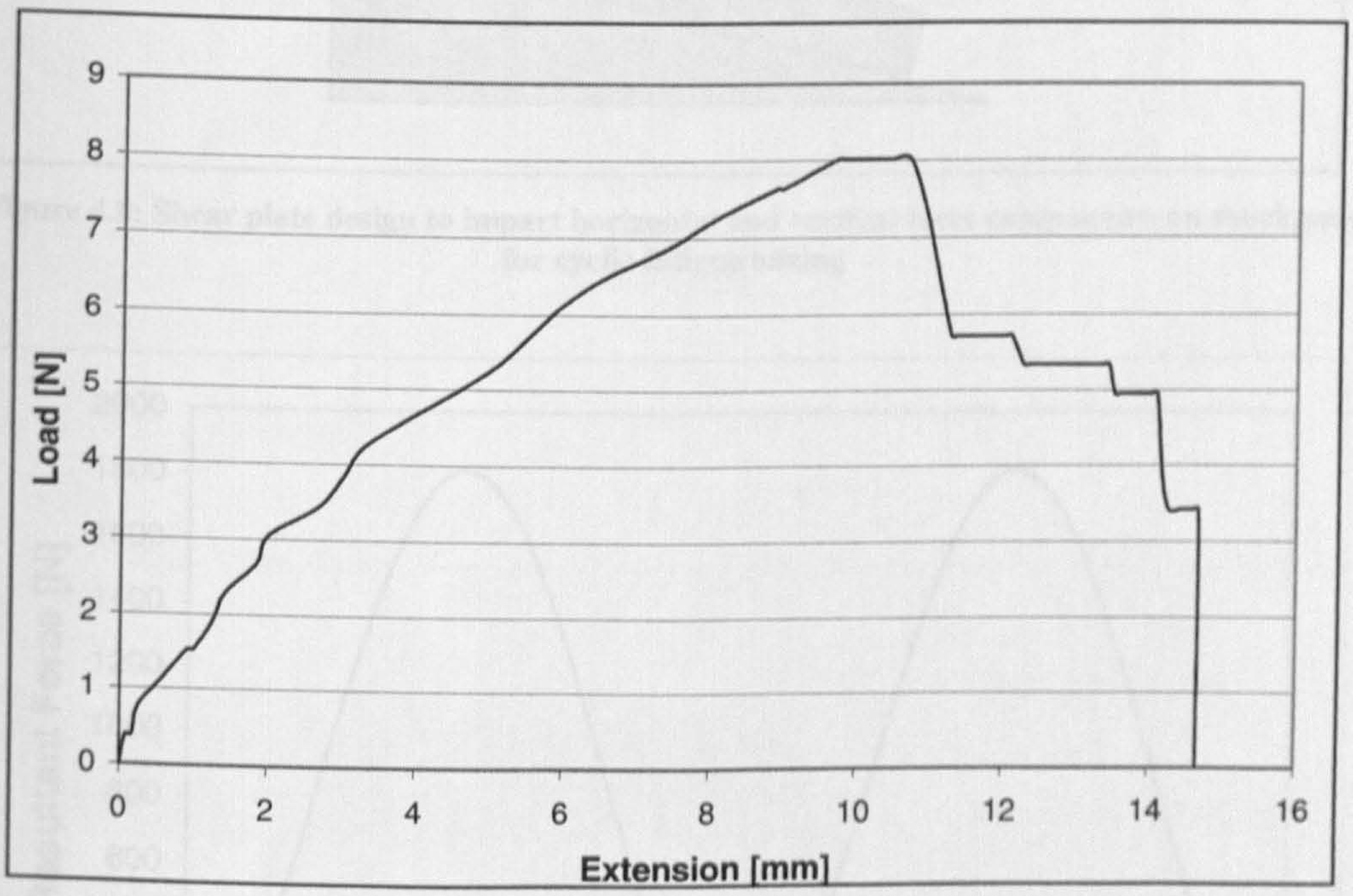


Figure 4.7: Typical load-extension graph for the tensile testing of shockpads.

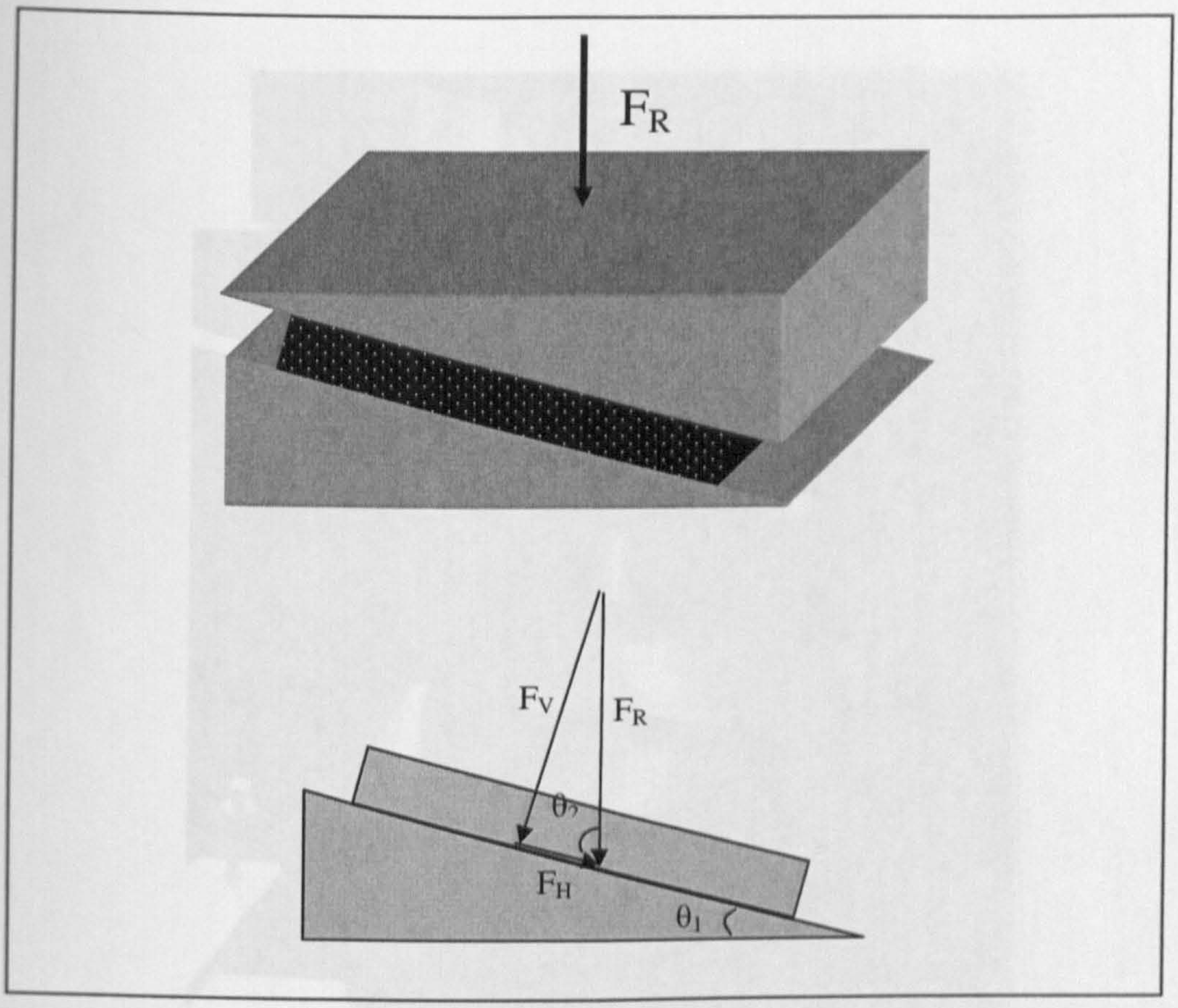


Figure 4.8: Shear plate design to impart horizontal and vertical force components on shockpads for cyclic fatigue testing

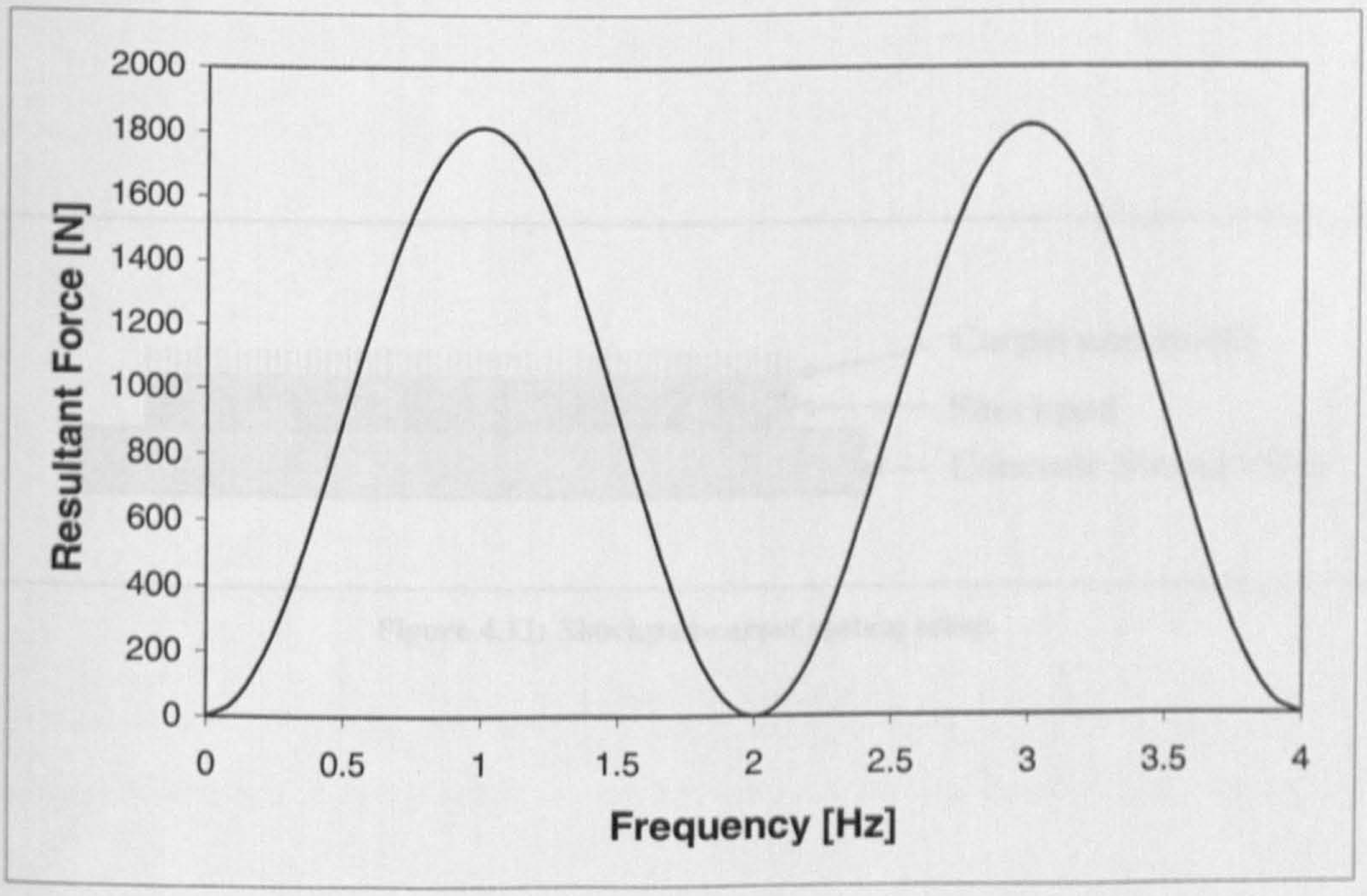


Figure 4.9: Representation of two loading cycles applied by the Dartec cyclic fatigue machine

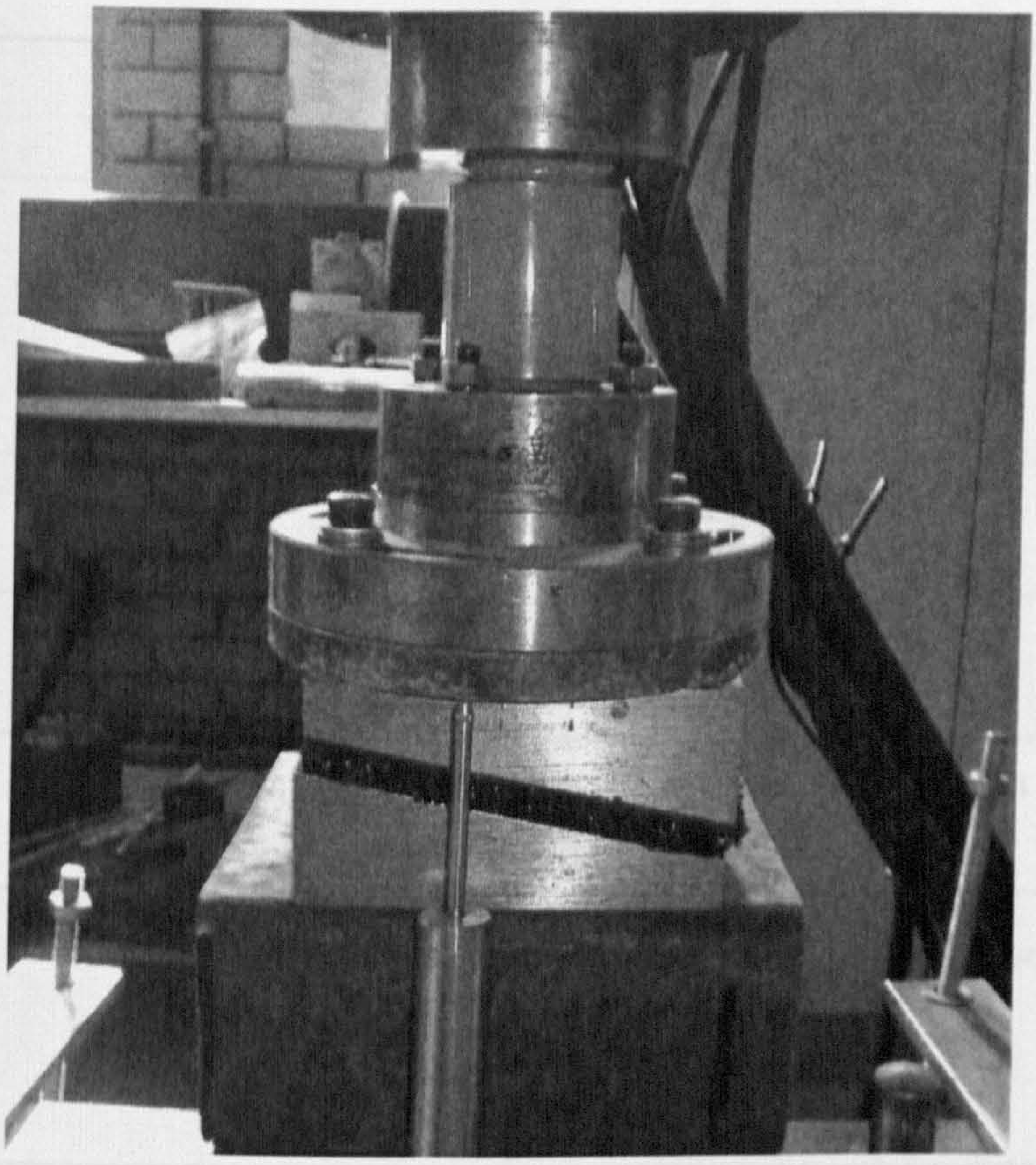


Figure 4.10: Dartec machine set-up with shockpad position within the shear plates shown and LVDT setup.

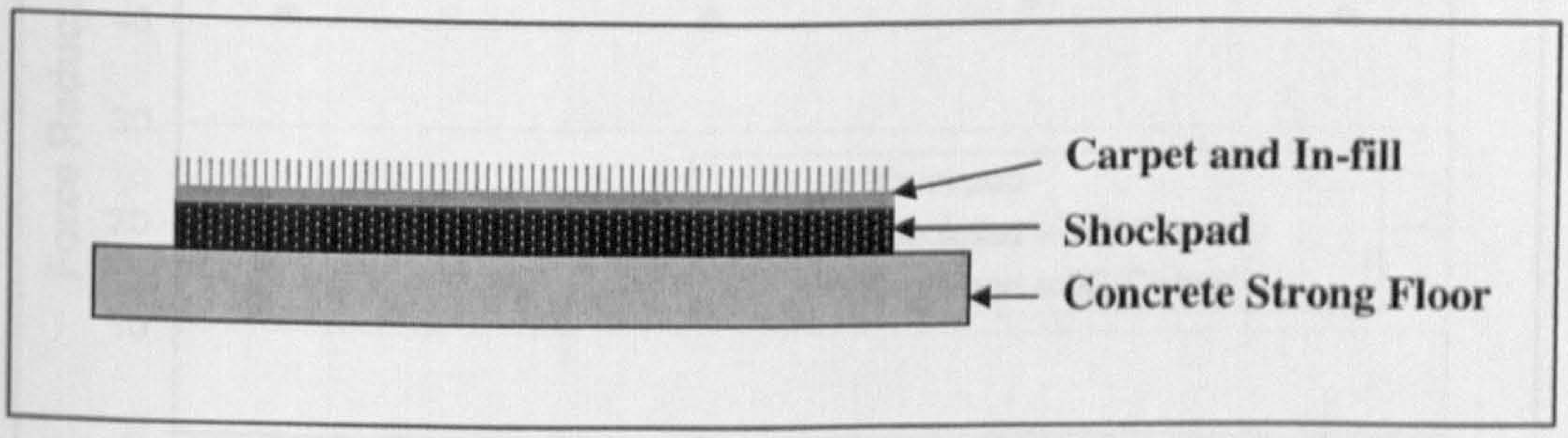


Figure 4.11: Shockpad-carpet system setup.

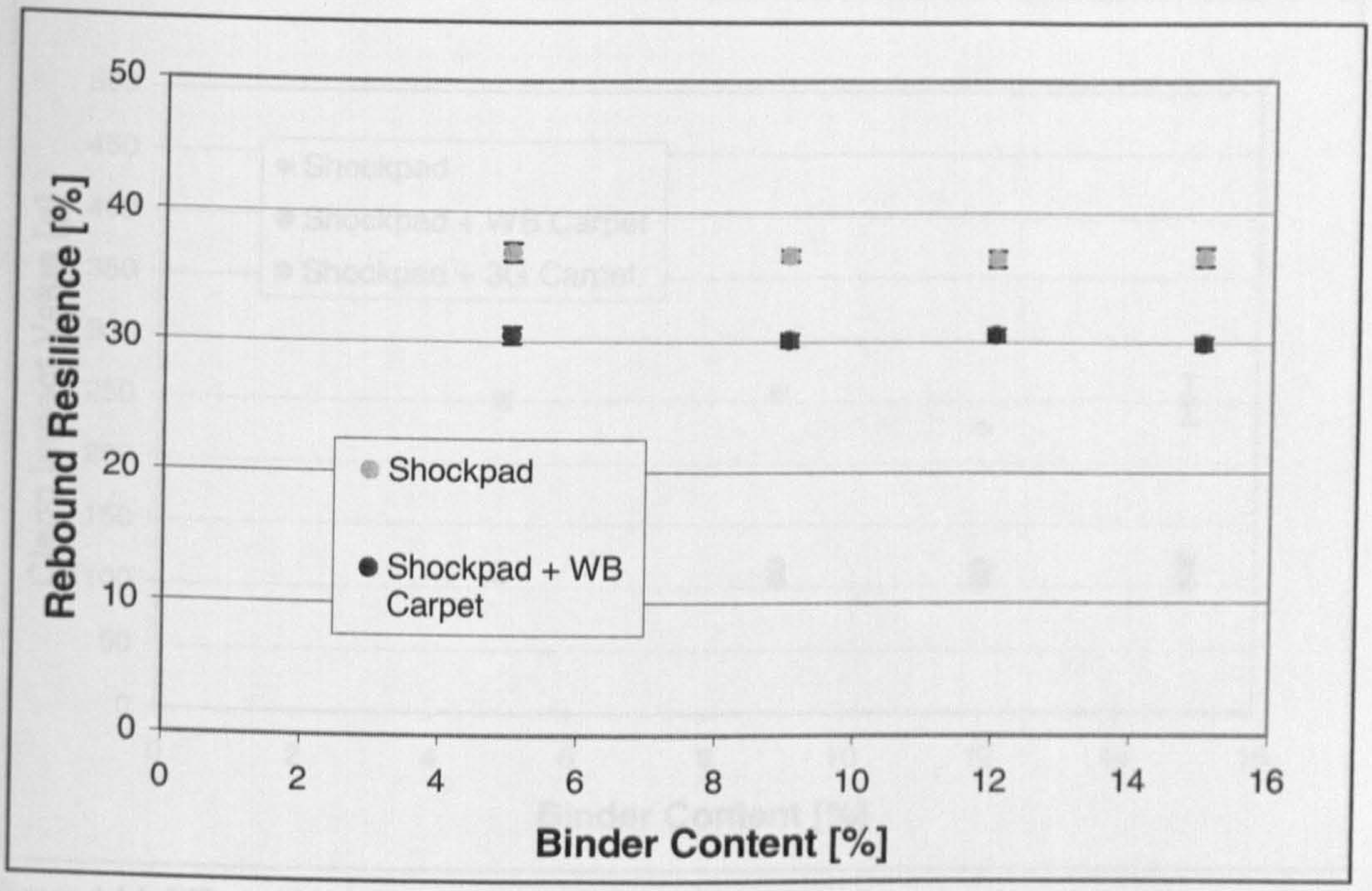


Figure 4.12: Effect of binder content on vertical hockey ball rebound resilience for shockpads and shockpad-water based carpet system

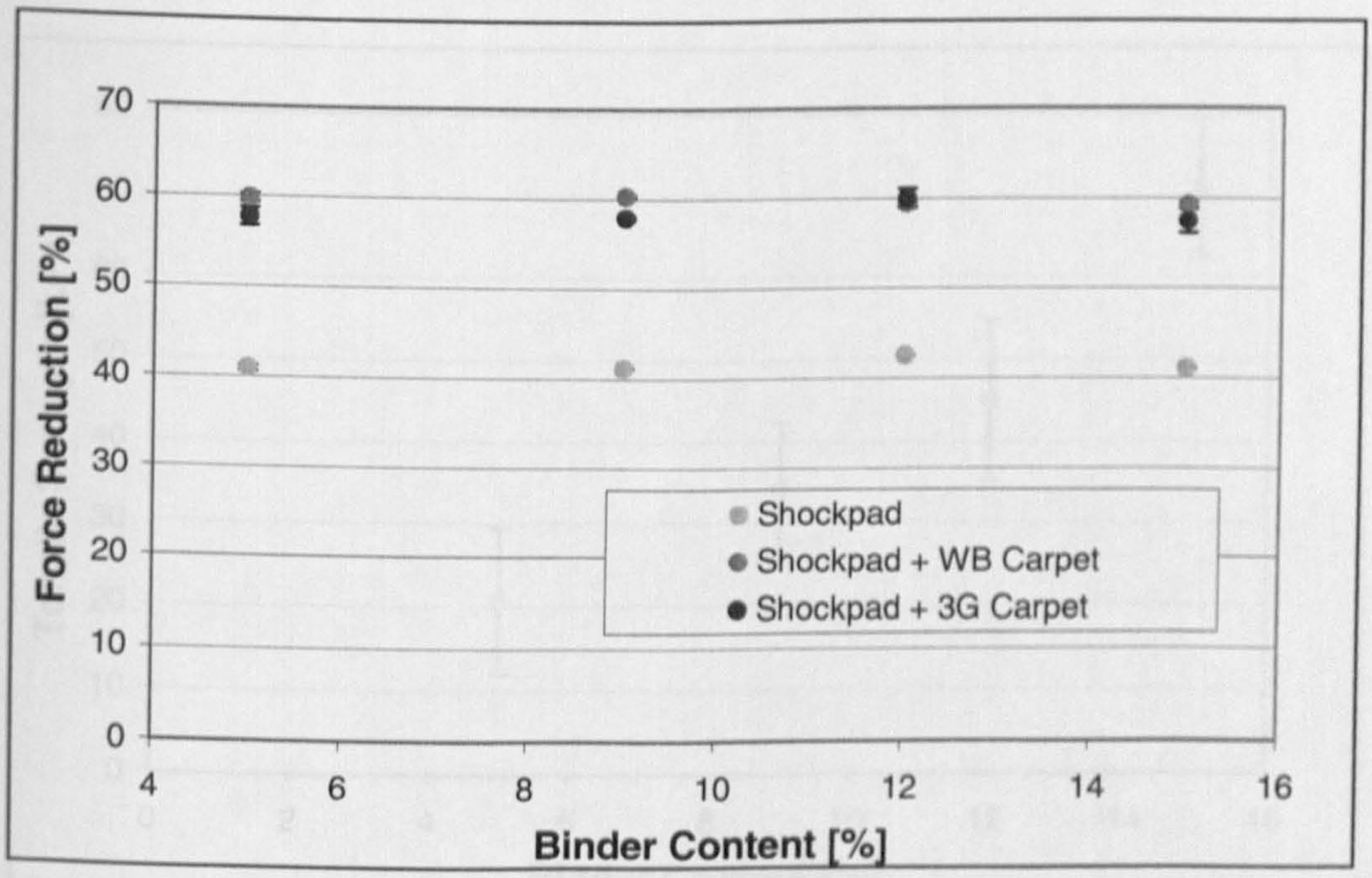


Figure 4.13: Effect of binder content on vertical force reduction for shockpads and shockpad-carpet systems.

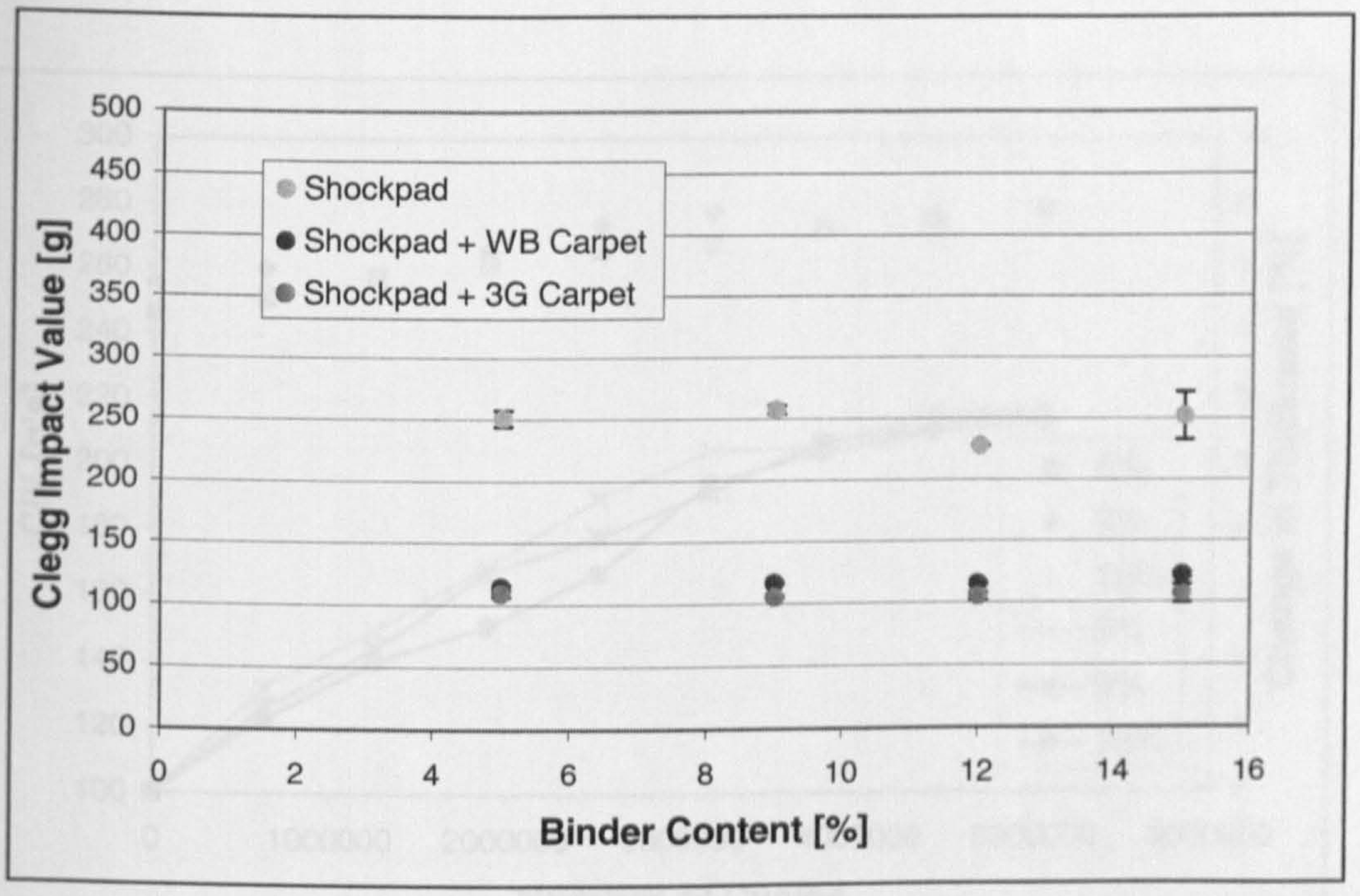


Figure 4.14: Effect of binder content on Clegg impact values of shockpads and shockpad-carpet systems.

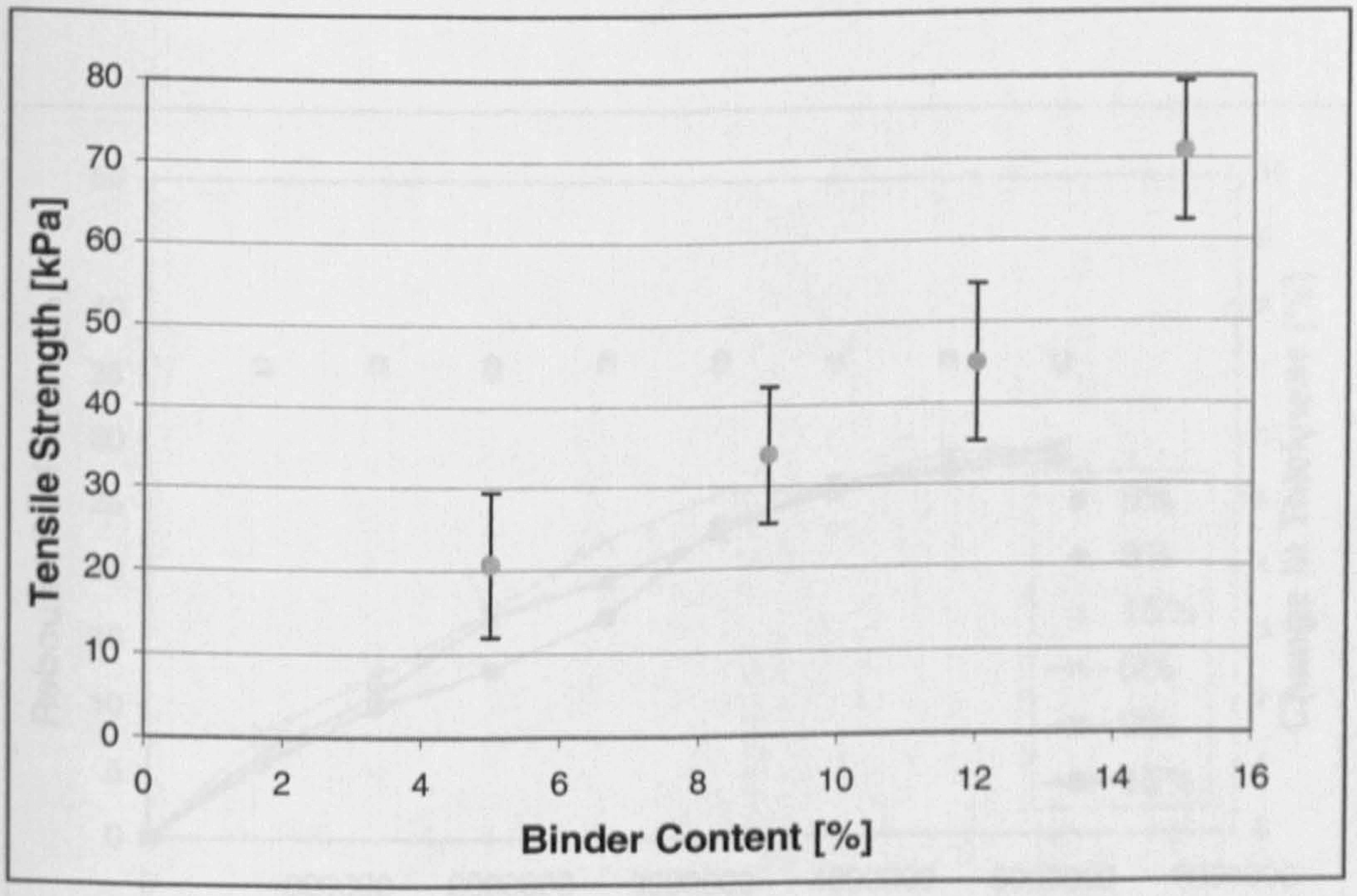


Figure 4.15: Effect of binder content on tensile strength of shockpads.

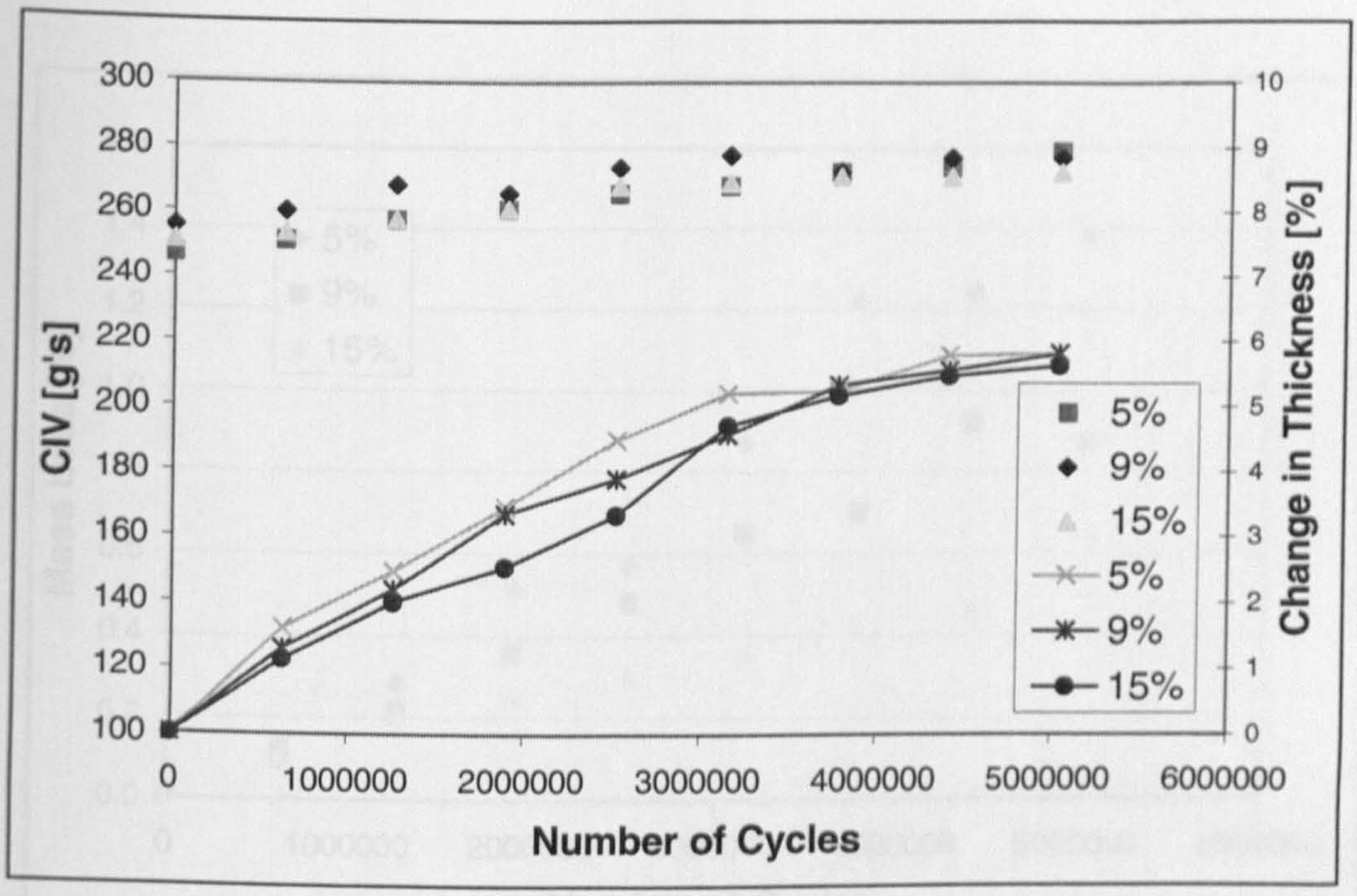


Figure 4.16: Effect of binder content on Clegg Impact Value and change in thickness during Cyclic Fatigue testing. Joined data points denote change in shockpad thickness. Each data point represents one year

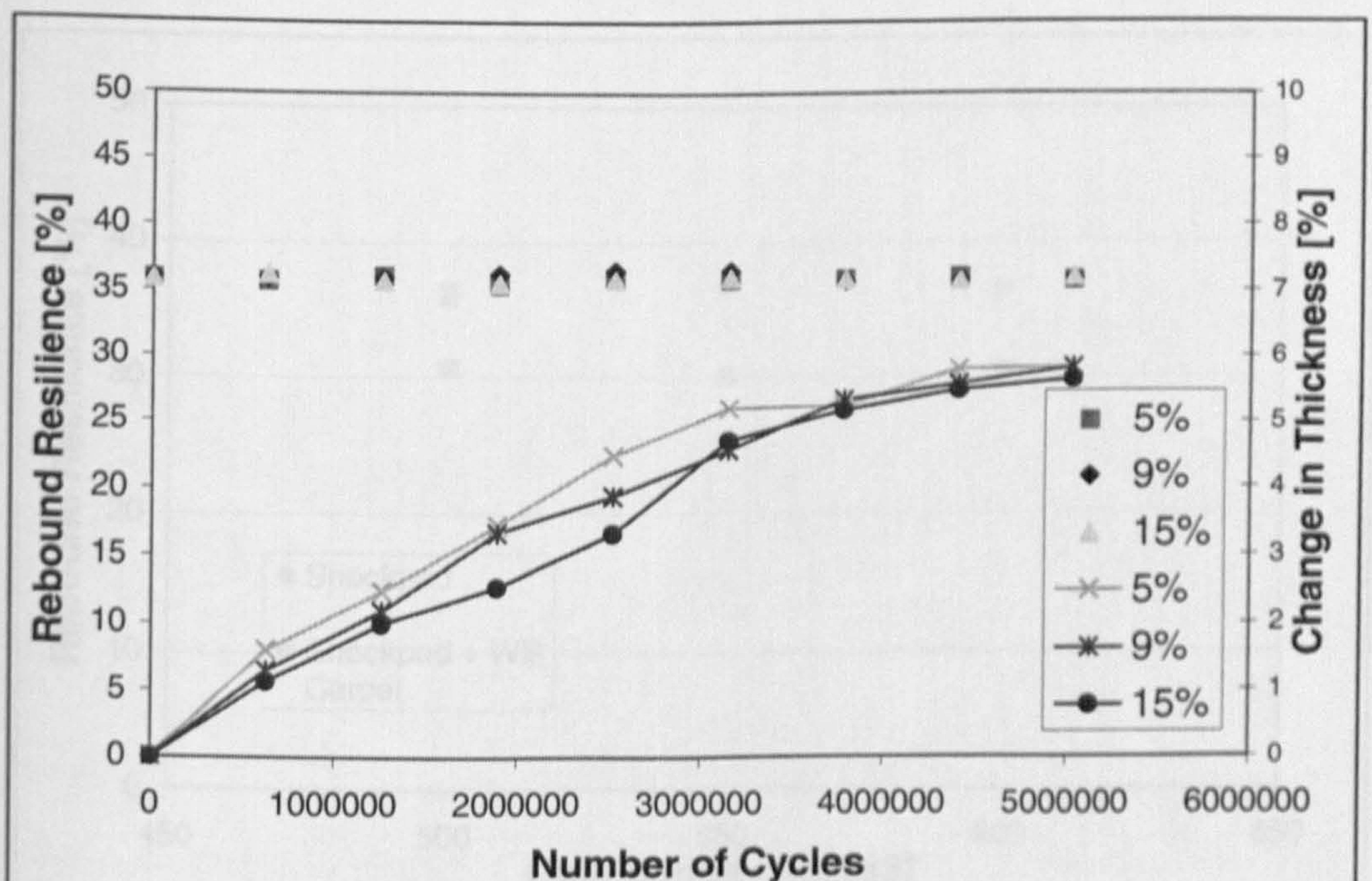


Figure 4.17: Effect of binder content on hockey ball rebound resilience and change in thickness during Cyclic Fatigue testing. Joined data points denote change in shockpad thickness.

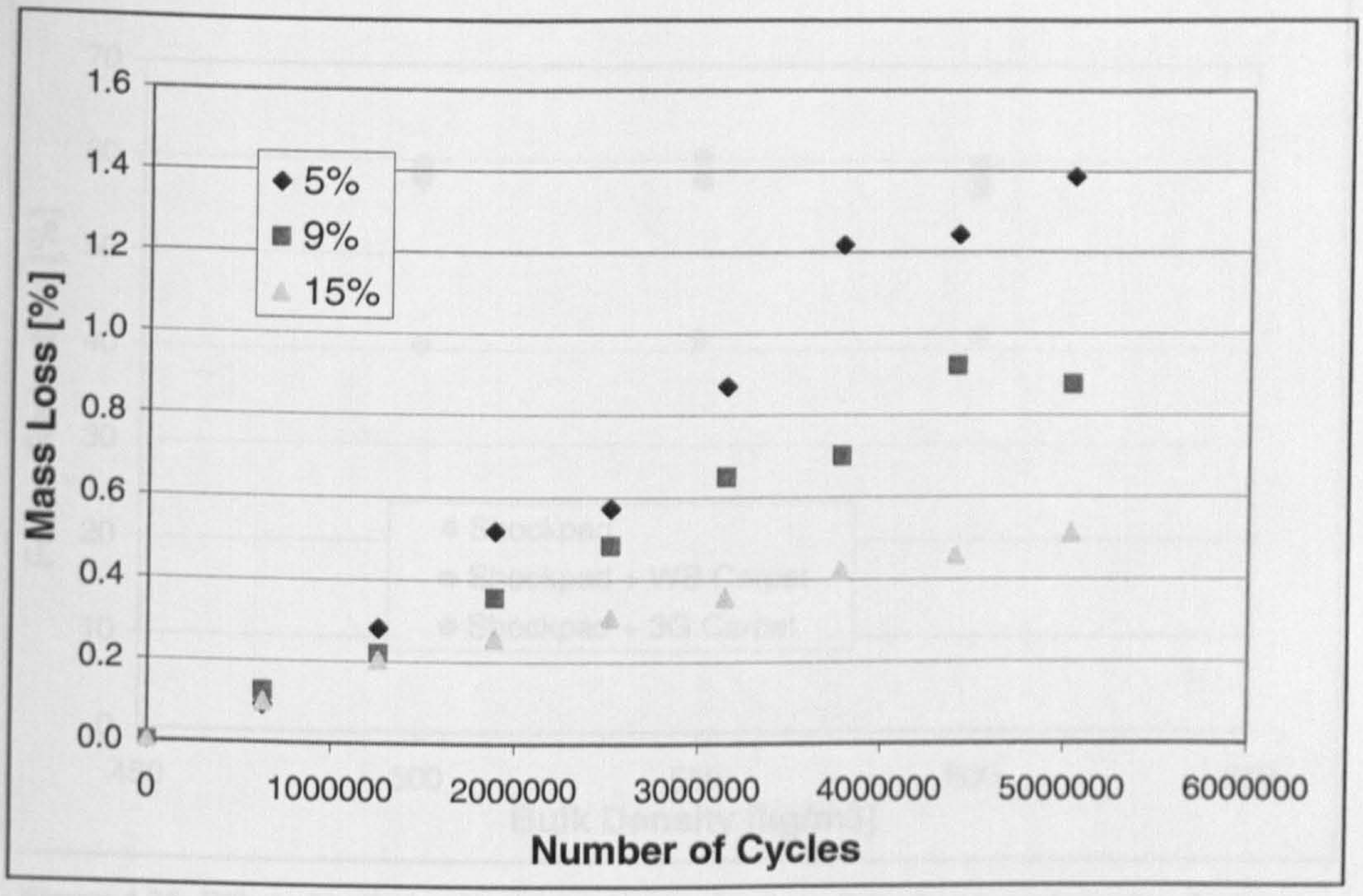


Figure 4.18: Effect of binder content on shockpad mass loss during Cyclic Fatigue testing

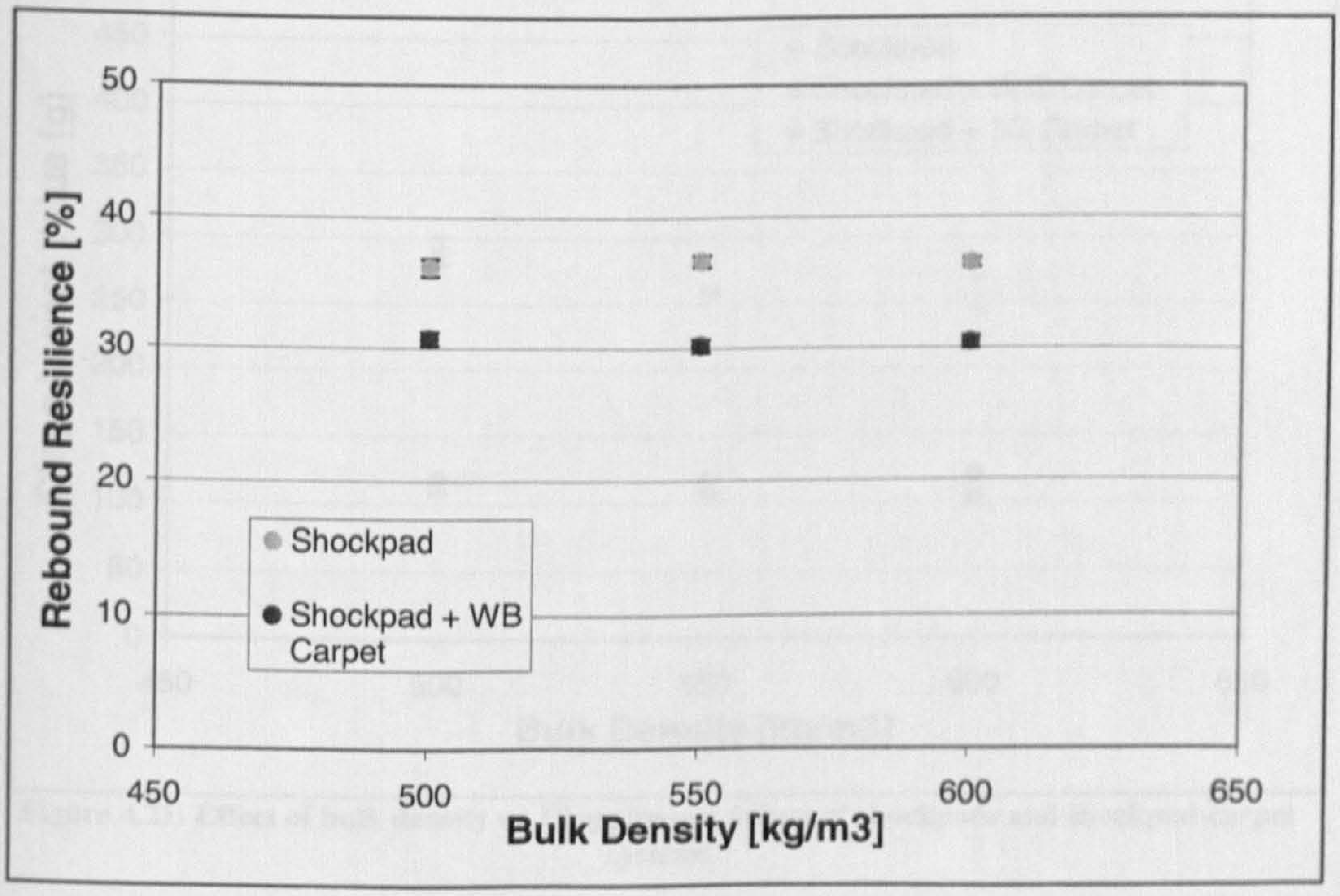


Figure 4.19: Effect of bulk density on the vertical ball rebound resilience of shockpads and shockpad-water based carpet system

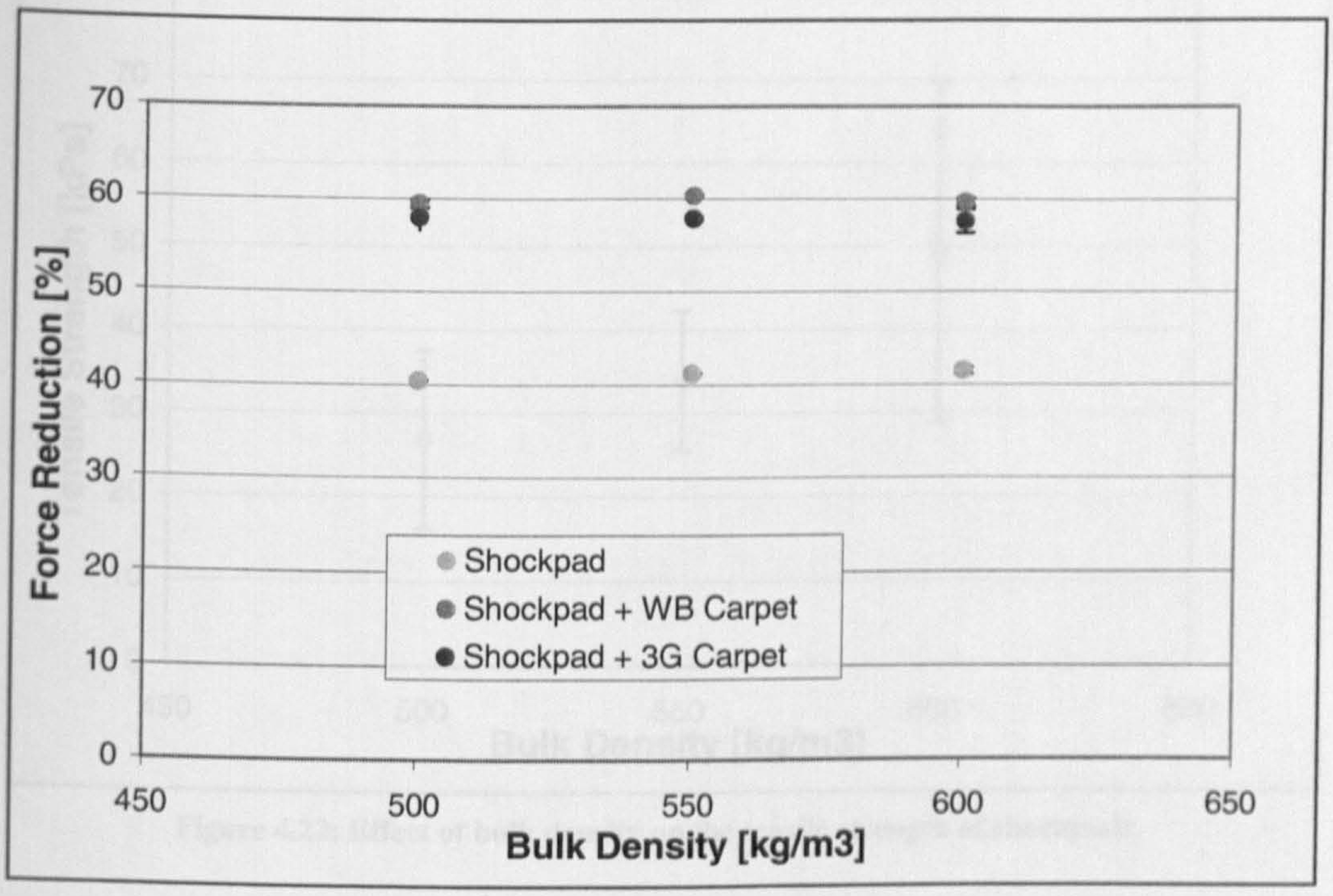


Figure 4.20: Effect of bulk density on the force reduction of shockpads and shockpad-carpet systems.

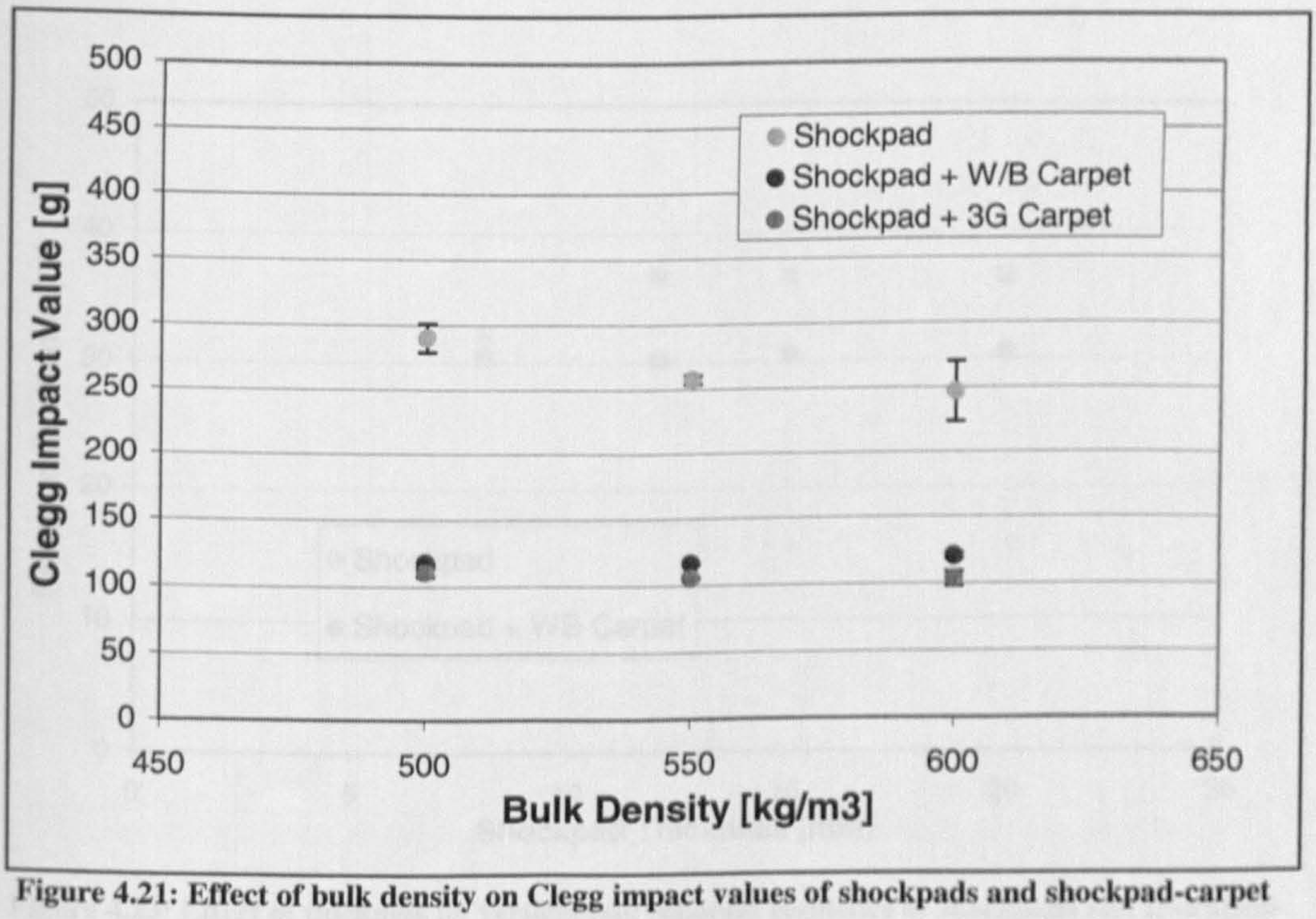


Figure 4.21: Effect of bulk density on Clegg impact values of shockpads and shockpad-carpet systems

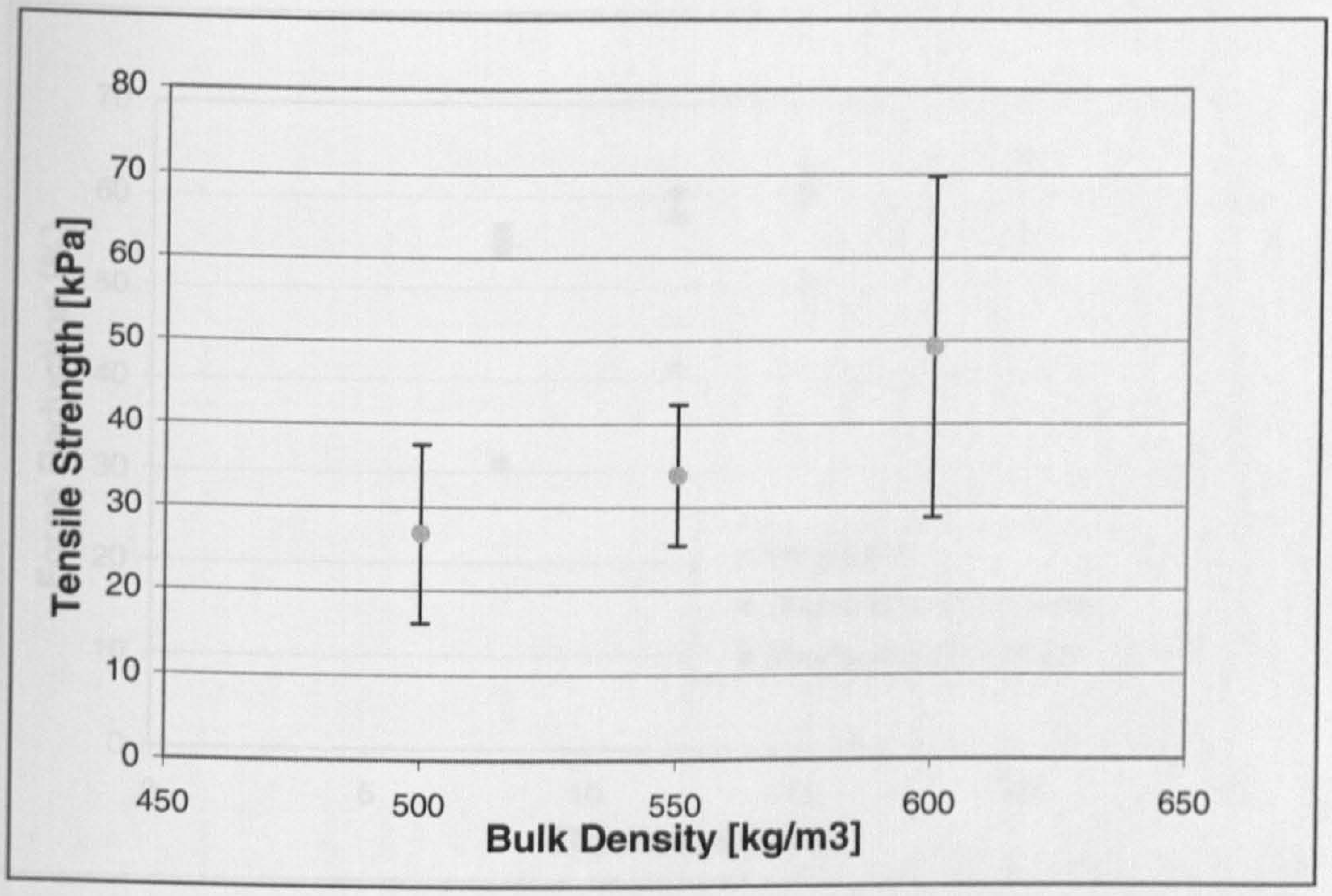


Figure 4.22: Effect of bulk density on the tensile strength of shockpads.

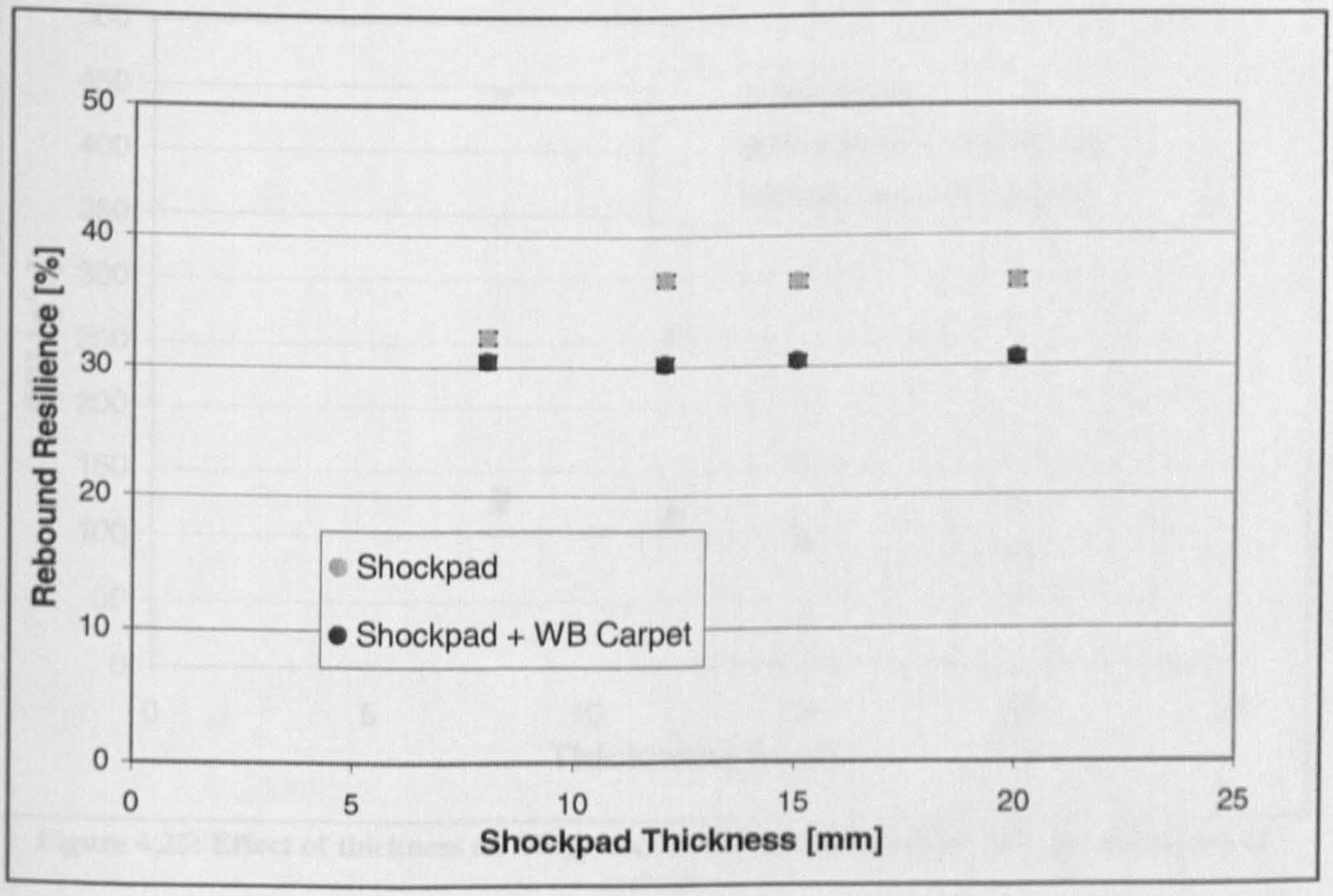


Figure 4.23: Effect of thickness on vertical ball rebound resilience of shockpads and shockpad-water based carpet system

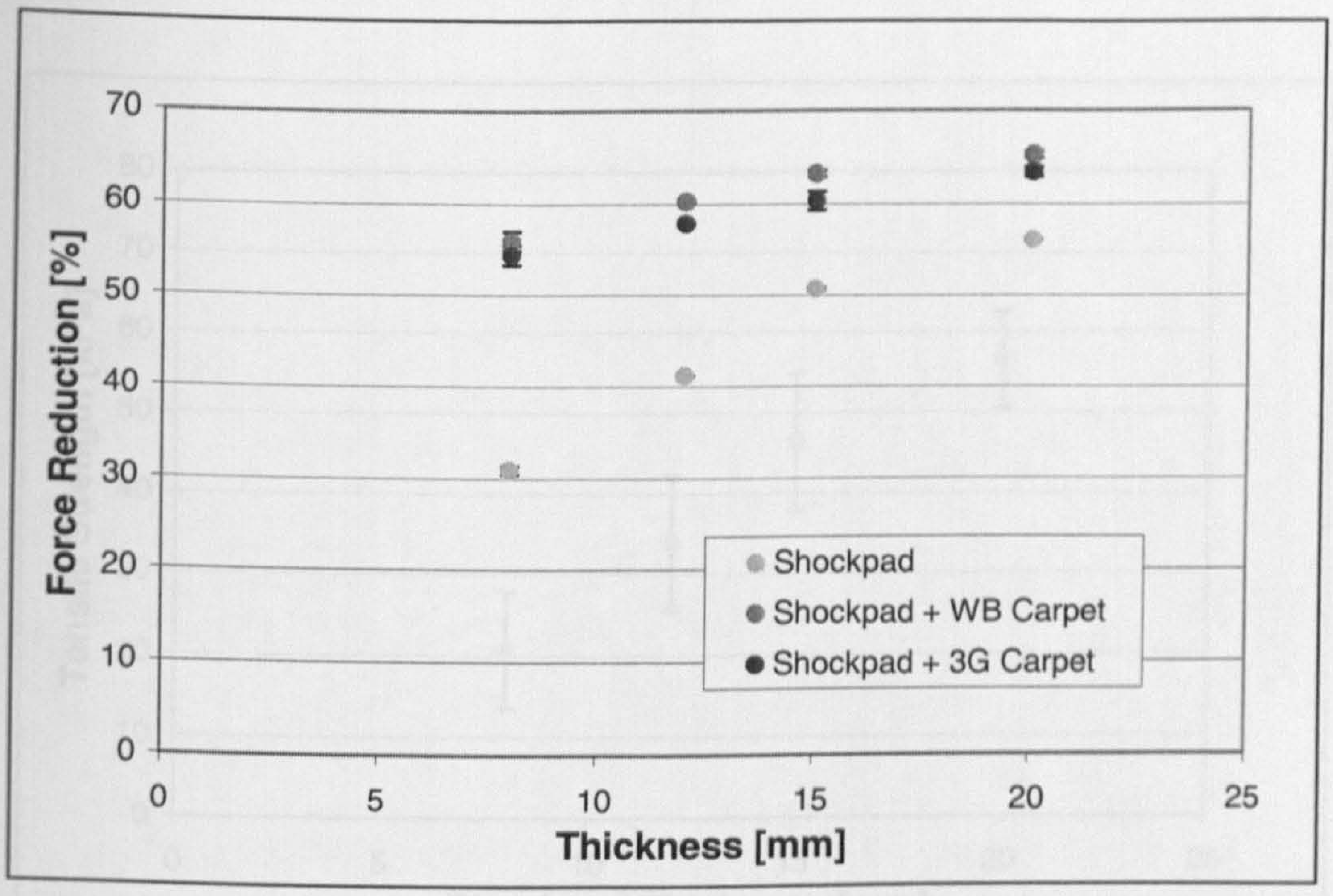


Figure 4.24: Effect of thickness on force reduction of shockpads and shockpad-carpet systems

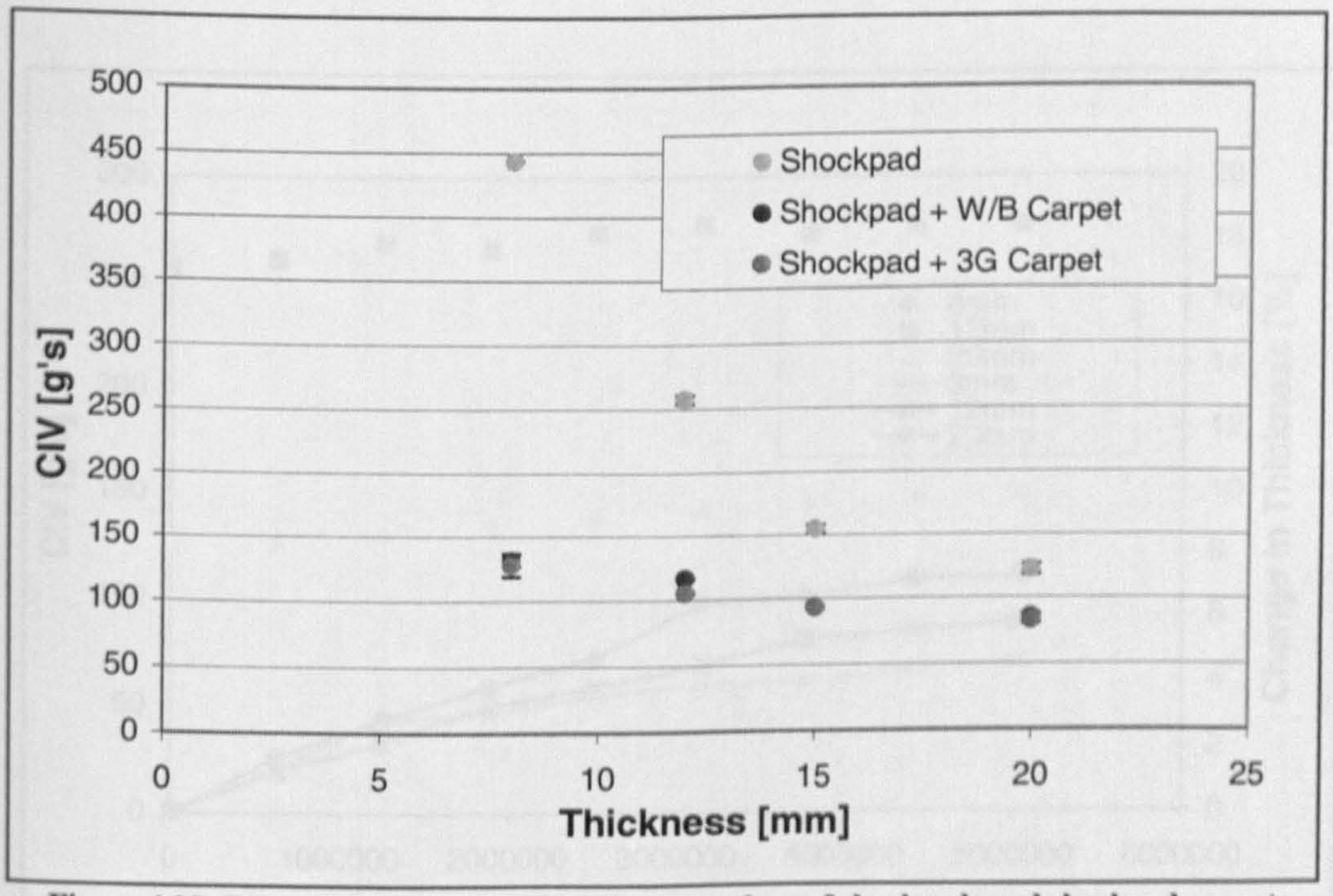


Figure 4.25: Effect of thickness on Clegg impact values of shockpads and shockpad-carpet systems

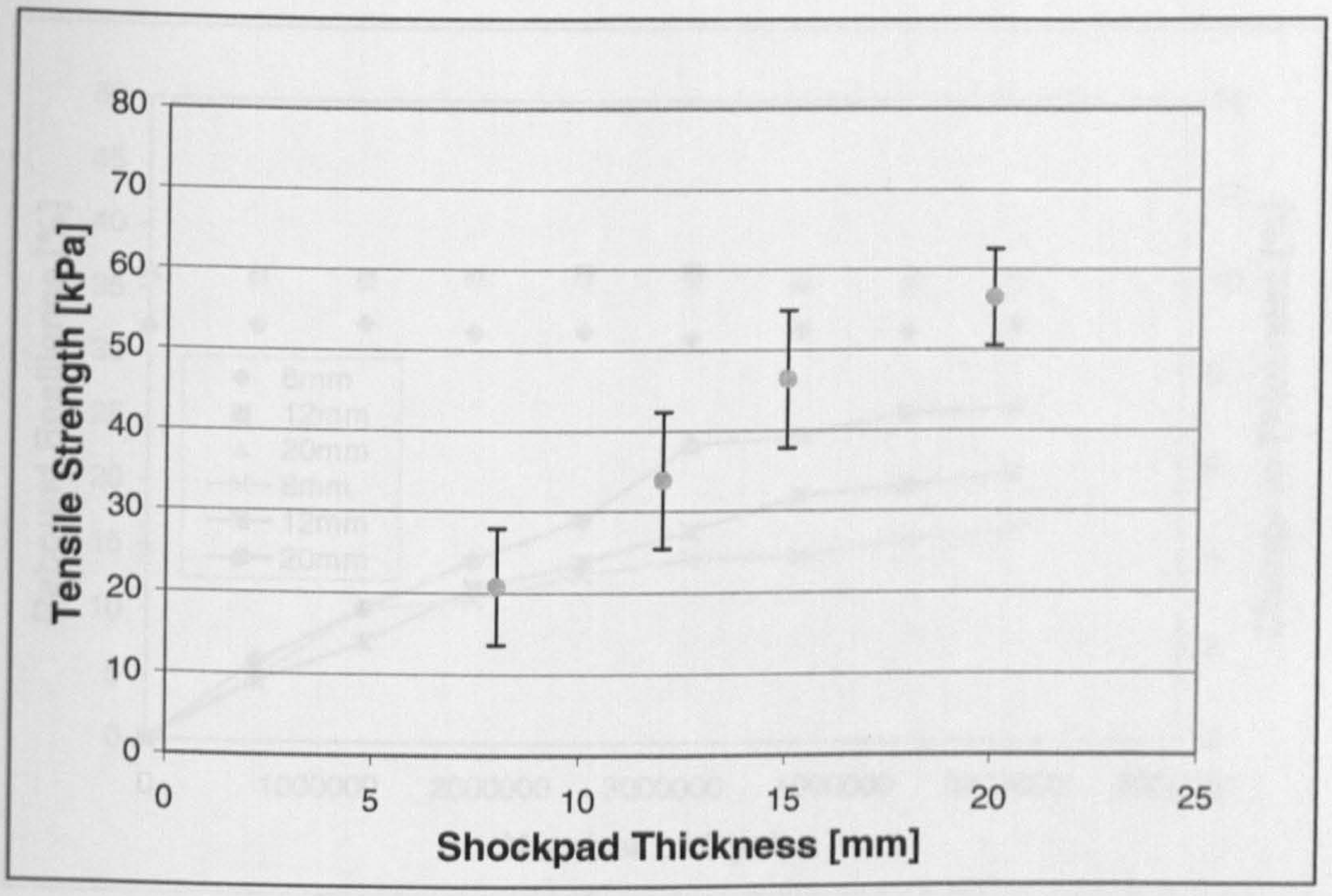


Figure 4.26: Effect of thickness on tensile strength of shockpads

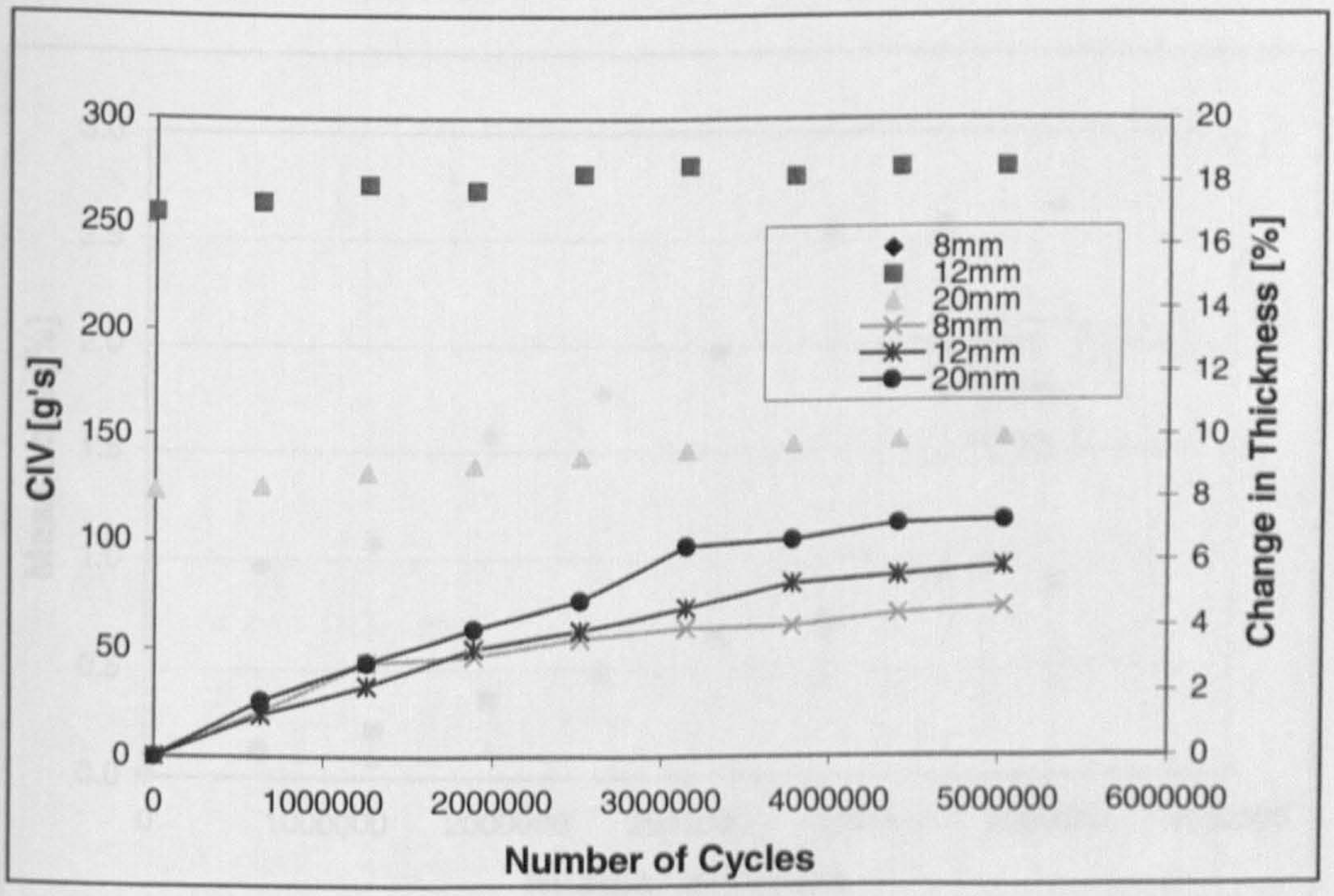


Figure 4.27: Effect of shockpad thickness on Clegg Impact Value and change in thickness during Cyclic Fatigue testing

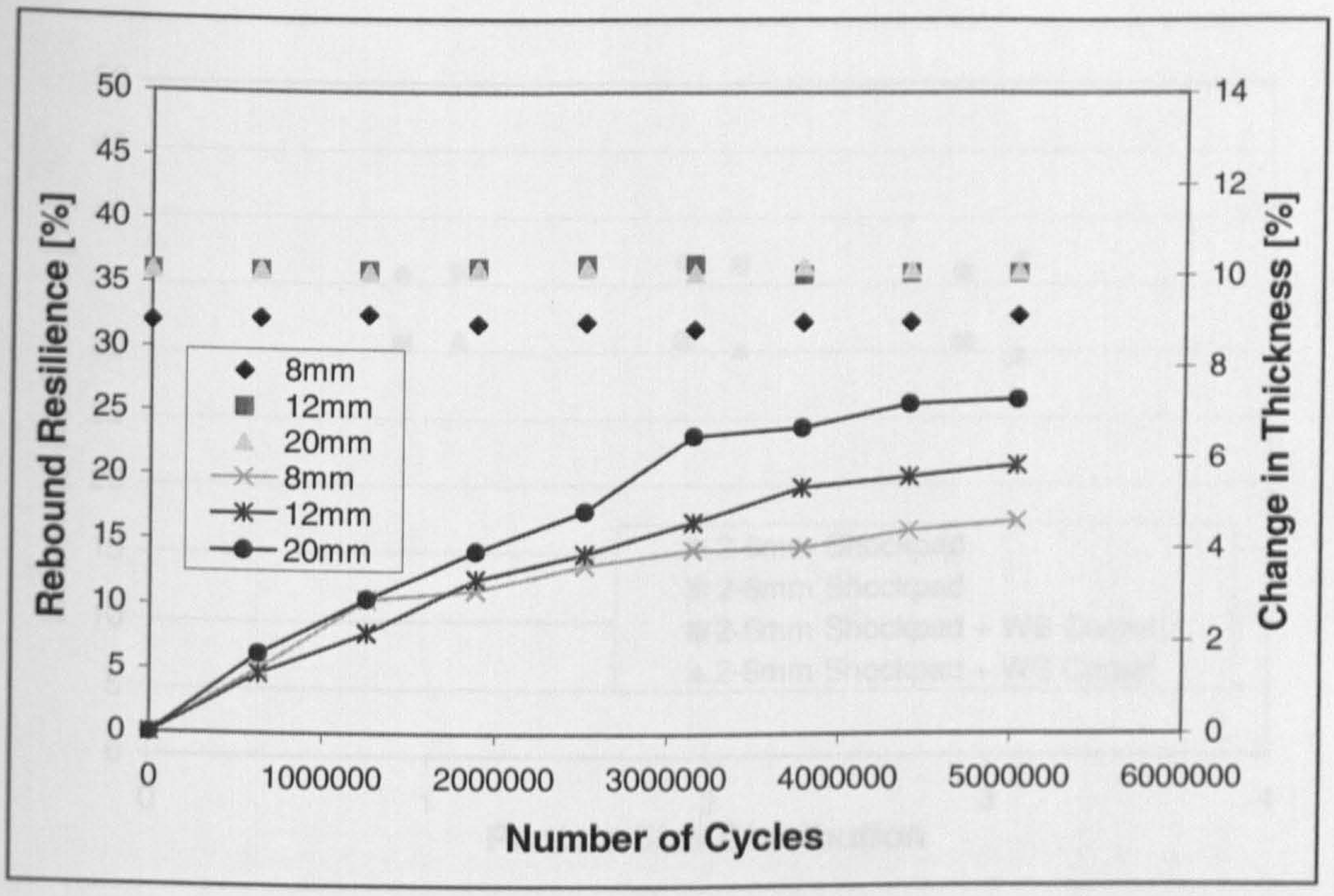


Figure 4.28: Effect of shockpad thickness on hockey ball rebound resilience and change in thickness during Cyclic Fatigue testing. Joined data points denote change in shockpad thickness.

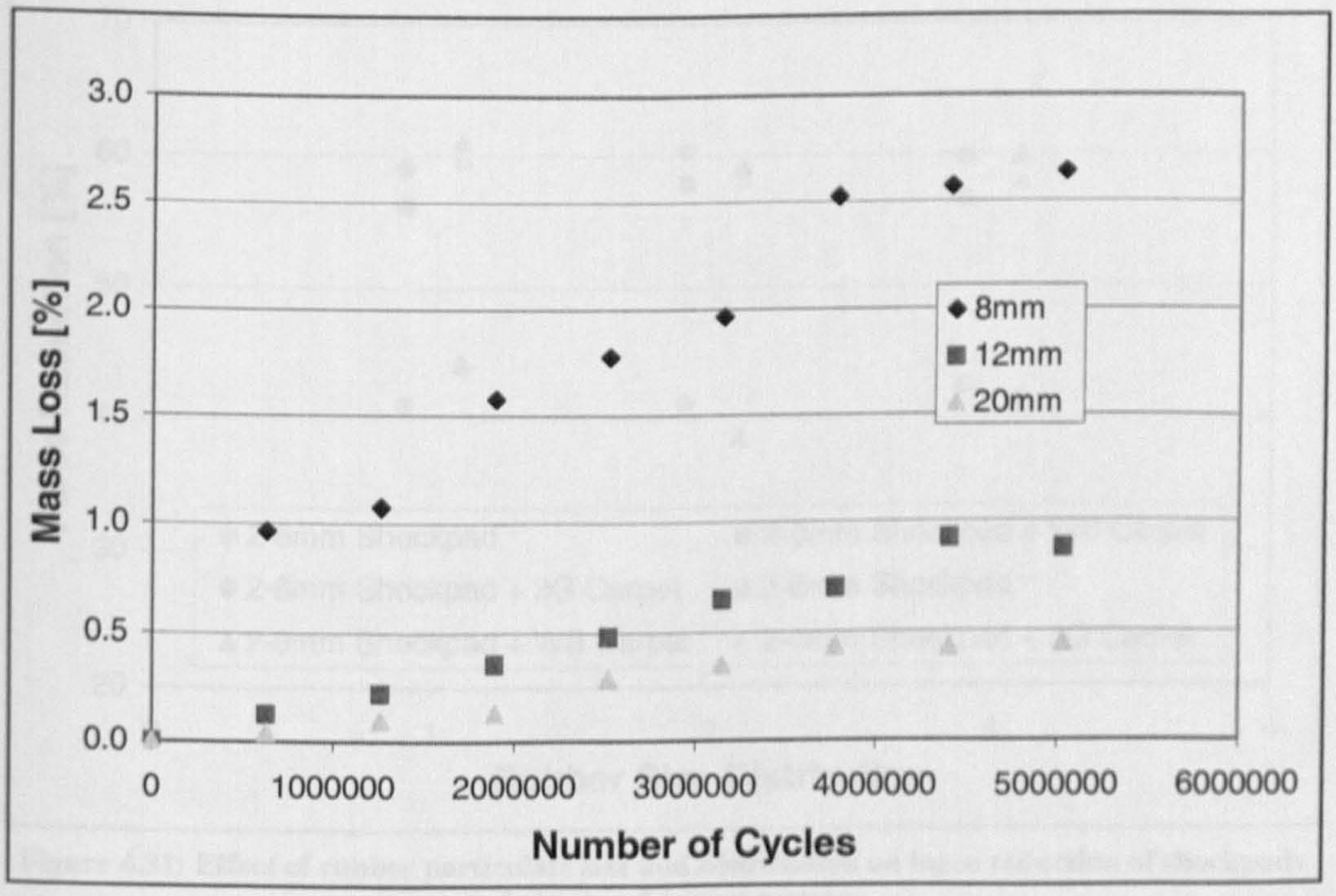


Figure 4.29: Effect of shockpad thickness on shockpad mass loss during Cyclic Fatigue testing

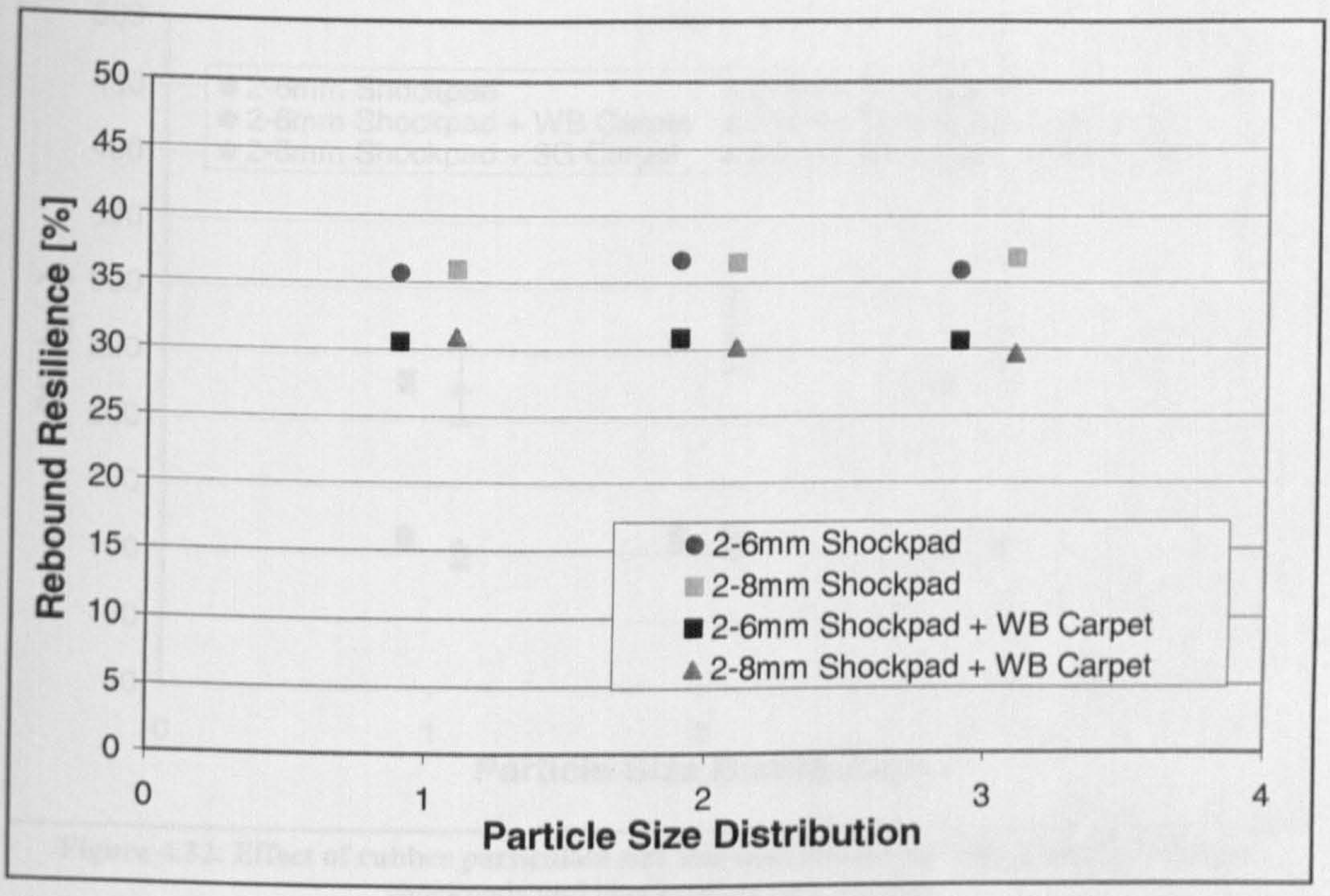


Figure 4.30: Effect of rubber particulate size and distribution on vertical ball rebound resilience of shockpads and shockpad-water based hockey carpet system

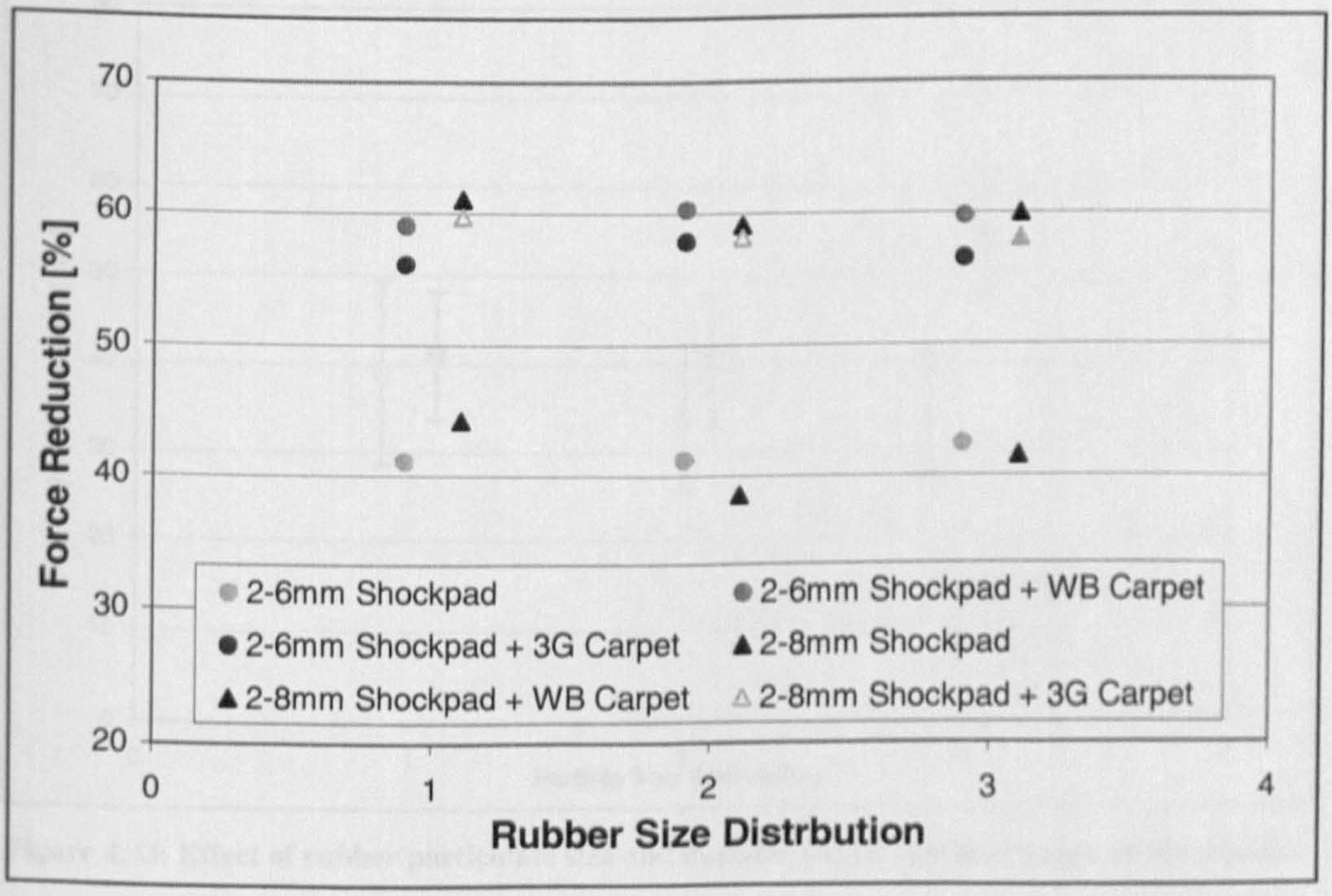


Figure 4.31: Effect of rubber particulate size and distribution on force reduction of shockpads and shockpad-carpet systems

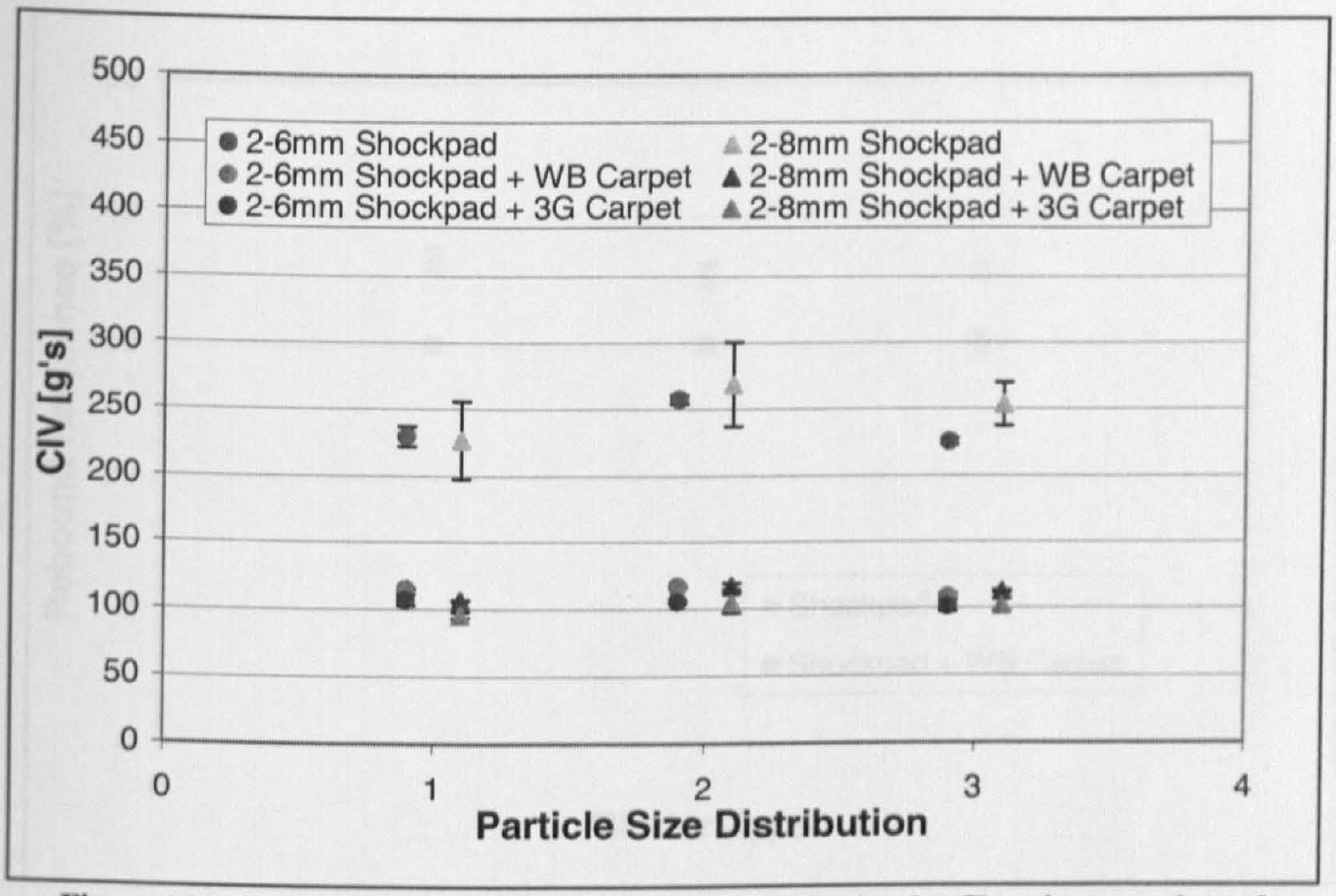


Figure 4.32: Effect of rubber particulate size and distribution for Clegg impact values of shockpads and shockpad-carpet systems

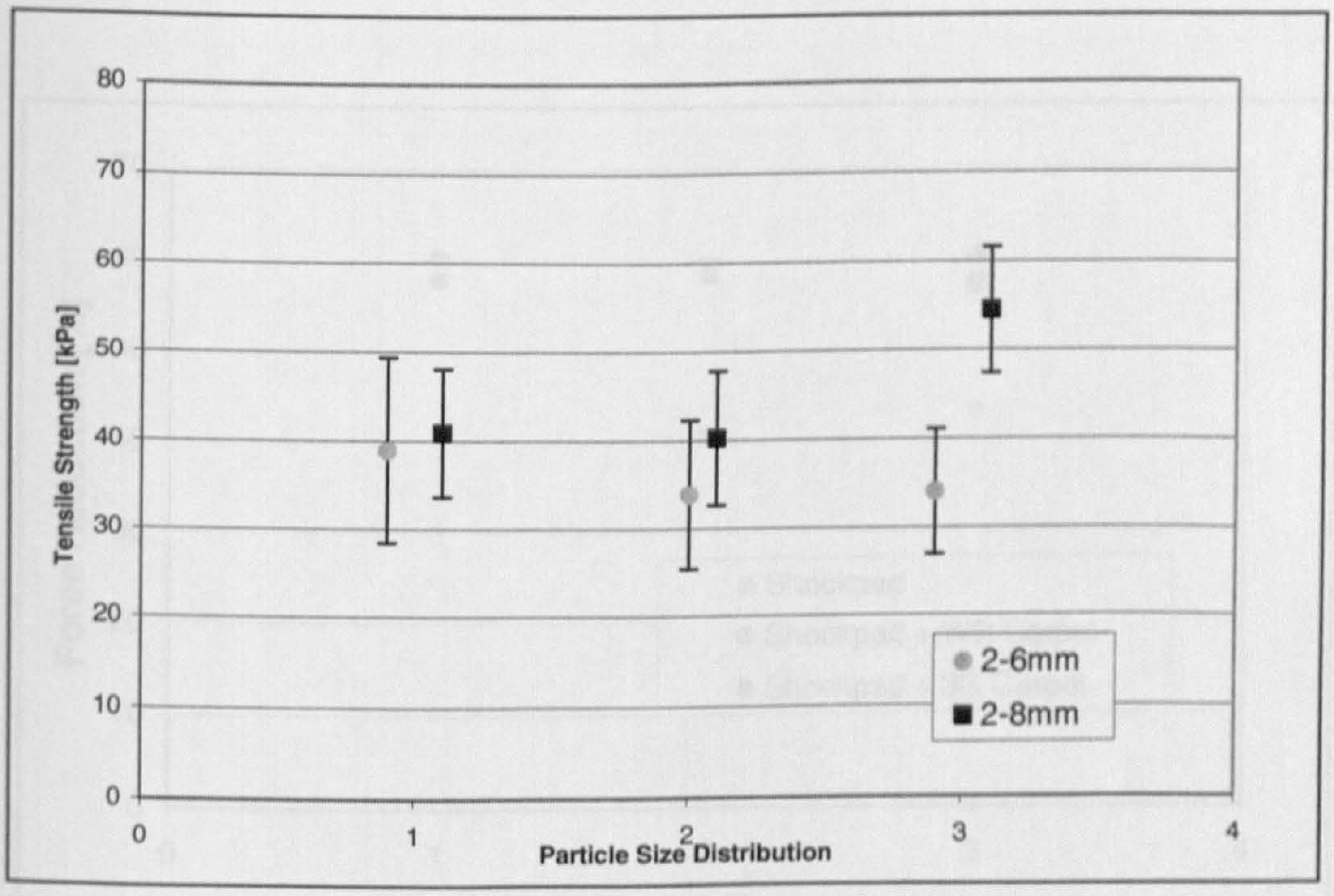


Figure 4.33: Effect of rubber particulate size and distribution on tensile strength of shockpads.

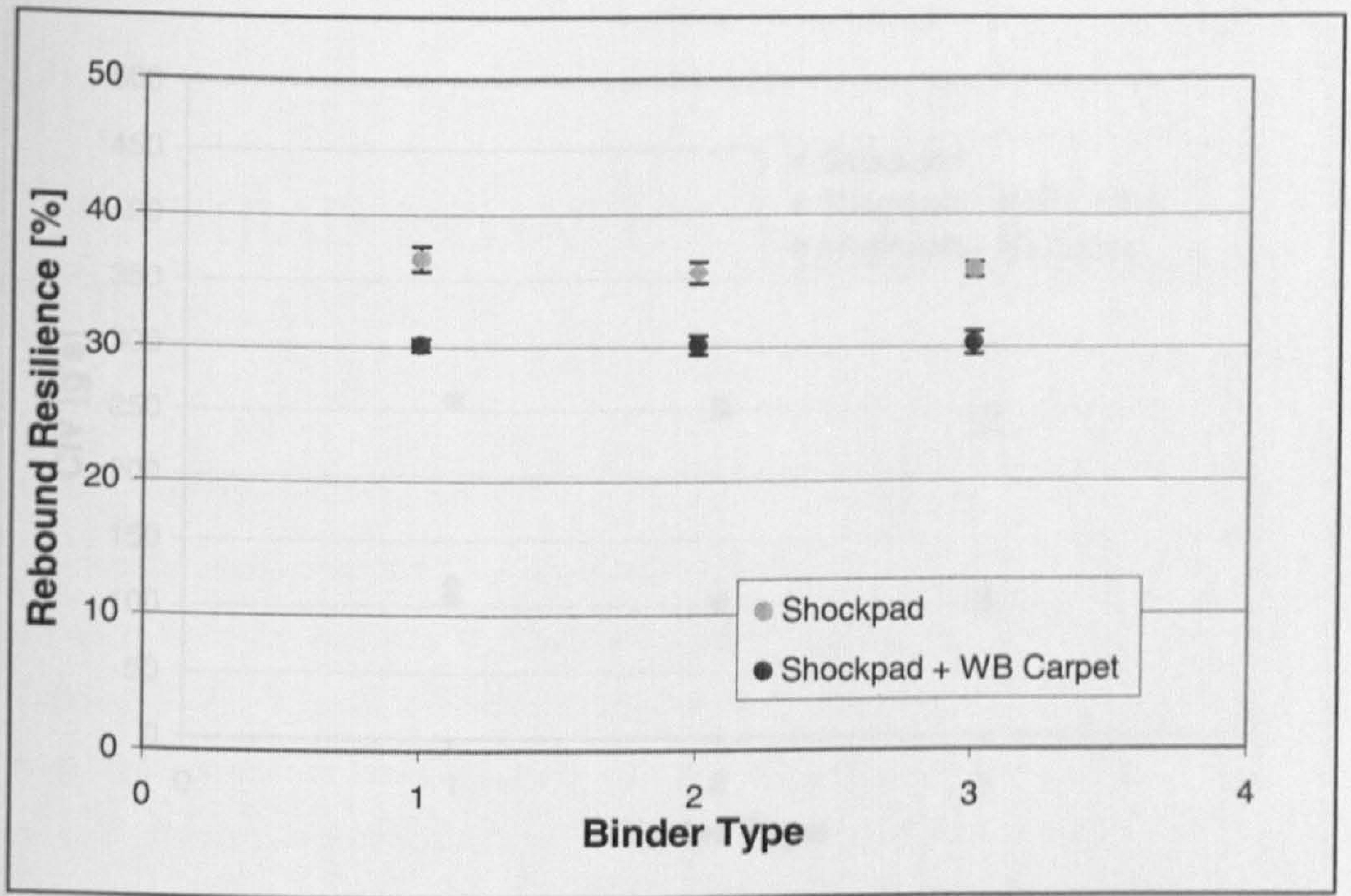


Figure 4.34: Effect of binder type on vertical ball rebound resilience of shockpads and shockpad-water based carpet system

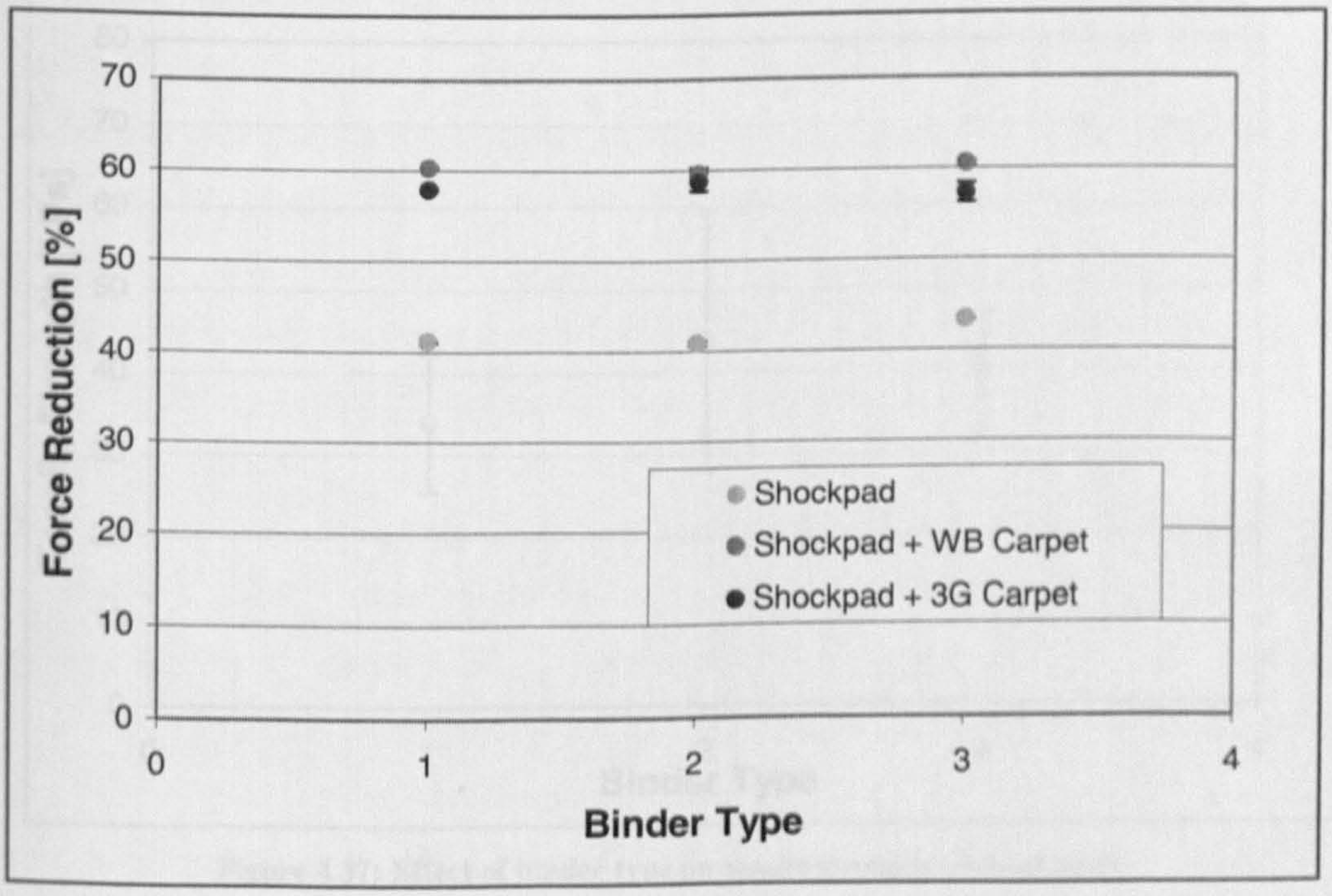


Figure 4.35: Effect of binder type on force reduction of shockpads and shockpad-carpet systems

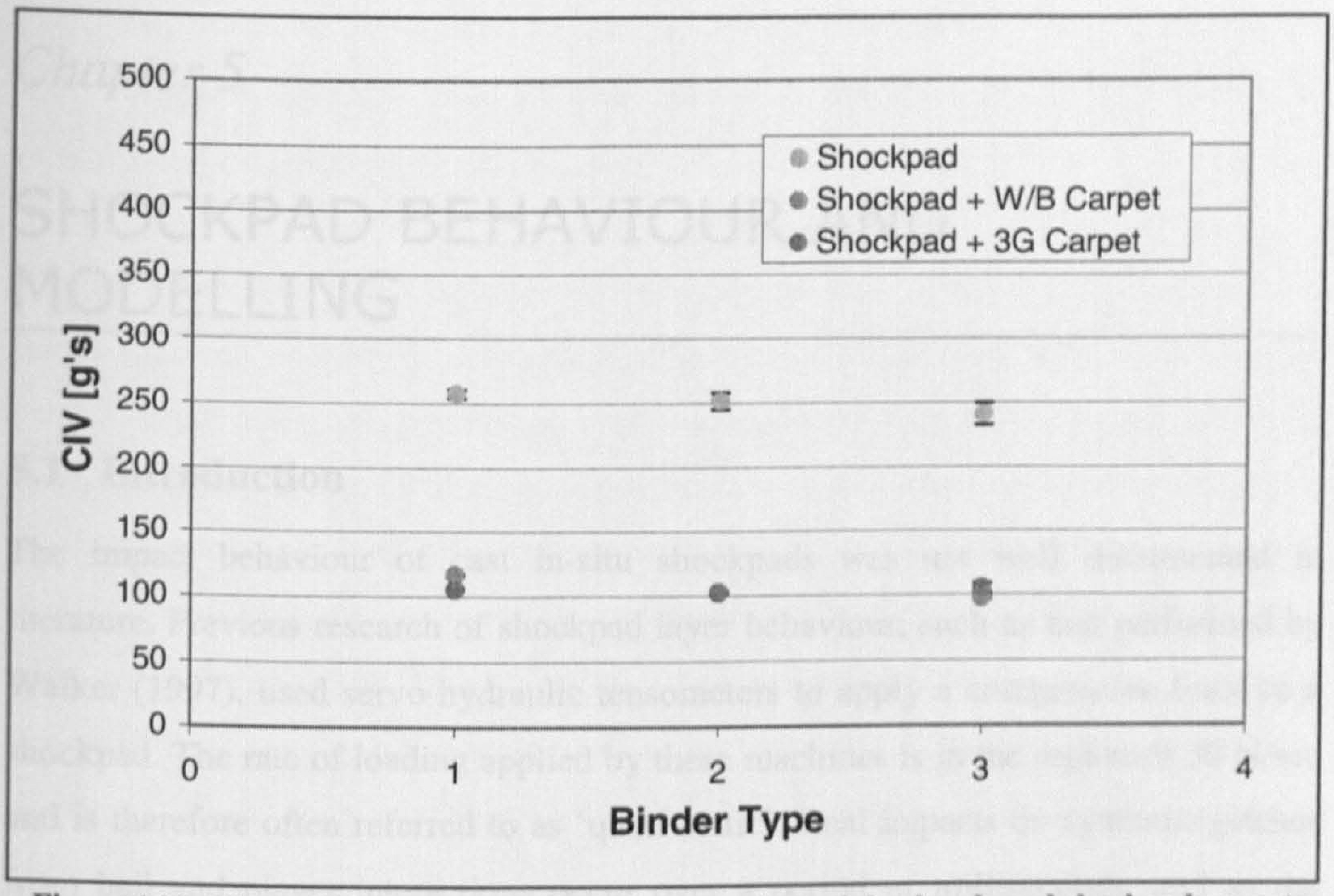


Figure 4.36: Effect of binder type on Clegg impact values of shockpads and shockpad-carpet systems

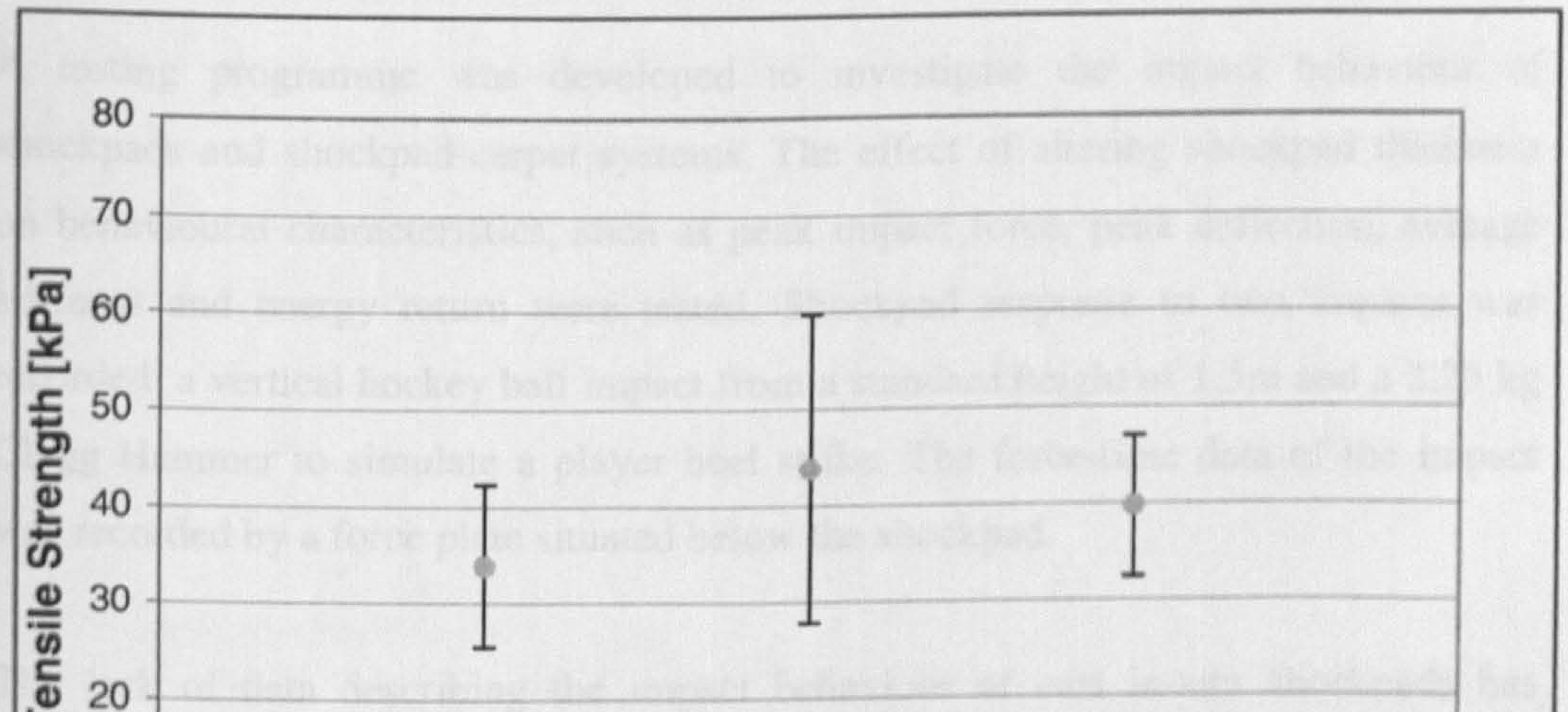


Figure 4.37: Effect of binder type on tensile strength of shockpads

Chapter 5

SHOCKPAD BEHAVIOUR AND MODELLING

5.1 Introduction

The impact behaviour of cast in-situ shockpads was not well documented in literature. Previous research of shockpad layer behaviour, such as that performed by Walker (1997), used servo-hydraulic tensometers to apply a compressive force to a shockpad. The rate of loading applied by these machines is in the region of 50 N/sec and is therefore often referred to as 'quasi-static'. Real impacts on synthetic pitches from ball and player interactions occur over a period of milliseconds, and as the behaviour of rubber, a major constituent of cast in-situ shockpads, is strain rate dependent, the actual behaviour of shockpads under impact conditions was unknown.

A testing programme was developed to investigate the impact behaviour of shockpads and shockpad-carpet systems. The effect of altering shockpad thickness on behavioural characteristics, such as peak impact force, peak deflection, average stiffness and energy return were tested. Shockpad response to two impacts was recorded; a vertical hockey ball impact from a standard height of 1.5m and a 2.25 kg Clegg Hammer to simulate a player heel strike. The force-time data of the impact was recorded by a force plate situated below the shockpad.

The lack of data describing the impact behaviour of cast in-situ shockpads has prevented a suitable model from being developed. McCullough (1985) identified models for foam layers used as shockpads described by a mechanical model represented by a non-linear spring and damper. The dissimilarity material structure and composition between the foam and recycled rubber particulate used in cast in-situ shockpads prevented the model coefficients of stiffness and damping, determined by McCullough, from being used to describe cast in-situ shockpads, but presented a basic model that is able to describe non-linear behaviour and hysteresis.

Five basic mechanical models, based on those presented by McCullough (1985), were compared to force plate data to determine the suitability of the model for describing shockpad behaviour.

Research into the impact behaviour of shockpads was aimed at assisting both the sports surfacing industry and academia. Knowledge of shockpad behaviour, and the factors which affect this behaviour, are beneficial to the sports surfacing industry in optimising their design for functional performance and producing consistency among pitch constructions. It is also anticipated to assist engineering and biomechanical research in providing a clearer understanding of the behaviour of the shockpad layer within a synthetic sports pitch and provide appropriate coefficients for whole pitch or player-surface interaction models. Advances in shockpad design through industry development and academic research will ultimately benefit synthetic pitch users.

This chapter is divided into two sections that deal with the measured impact behaviour of shockpads and mechanical modelling separately. The experimental methodology section describes the testing programme for both shockpad behaviour and mechanical modelling, however the results and discussion are provided separately. A summary is provided to draw the two sets of findings together. Findings from this chapter are also combined with findings from Chapters 3 and 4 in Chapter 6 to discuss overall findings from this research project.

5.2 Experimental Methodology

5.2.1 Introduction

The dynamic behaviour of shockpads and shockpad-carpet systems is not well documented in literature. The non linear, hysteretic nature of shockpad behaviour has been identified through quasi-static compression testing, however the strain rate dependence of shockpads prevents dynamic behaviour being fully understood using the quasi-static method.

Force plates are commonly used by biomechanics researchers to quantify impact forces generated from foot strike movements of players. The force transmitted to the plate during an impact is a measure of the stiffness and damping properties of materials placed on its upper surface. The force transducers below the plate are capable of high sampling rates (dependent on the loads being generated) producing accurate dynamic measurements of force against contact time.

A test programme was developed to measure the dynamic behaviour of shockpads and shockpad-carpet systems during impacts. Mechanical testing using a hockey ball and Clegg Hammer were used to create impacts as they are more repeatable than testing with human subjects. The resulting force-time data was to be converted to force-deflection data to assist in creating a wider understanding of shockpad behaviour in terms of the stress-strain relationship and energy return. A mechanical model of the force-deflection behaviour of shockpads and shockpad-carpet systems was to be developed from the force-deflection behaviour to describe and ultimately predict shockpad and shockpad-carpet system behaviour.

A range of shockpads and shockpad-carpet systems were identified for testing. Shockpad thickness was shown in Chapter 4 of this thesis to be the key mix design variable influencing shockpad mechanical properties and therefore warranted further investigation. Generic hockey and 3rd generation synthetic carpets were also shown to heavily influence mechanical properties and also warranted further investigation. The final test programme used hockey ball and Clegg Hammer impacts to investigate the general behaviour of benchmark shockpads and the behaviour of shockpads with variations in thickness ranging between 8 and 20 mm. The combined effect of the benchmark shockpad with generic hockey and 3rd generation carpets and the effect of generic carpets with a range of shockpad thickness were also investigated.

Force-time measurements collected from the force plate were converted to force-deflection data through a number of steps outlined in Figure 5.1. The raw impact data was filtered to remove noise and converted to acceleration by dividing force by the impactor's mass. Shockpad velocity and deflection were approximated through a series of integrations to produce force-deflection data. The force-deflection data was further converted to describe energy return and stress-strain behaviour.

Independent verification of impact data for ball impacts was provided by a comparison of high speed camera deflection measurements with deflection data derived from force plate measurements and also through a comparison of measured and predicted ball rebound heights. Verification of Clegg Hammer impacts was provided by a comparison of measurements recorded by its integrated accelerometer with acceleration data derived from force plate measurements.

A series of mechanical models were compared to data derived from the force plate to determine their suitability in accurately describing shockpad behaviour. The process is described in detail in the mechanical modelling section of this chapter.

5.2.2 Force Plate Data Acquisition

A Kistler force plate (9281B12) and interfaced computer were set up as shown in Figure 5.2. The force plate was set to trigger when a vertical load greater than 25 N was applied. Data was collected for a period of 1 second from the time of trigger to ensure data for all impacts was collected in their entirety. A pre-trigger of 10 msec was used to collect data prior to trigger to ensure the zero point was recorded for subsequent data analysis.

Data from each impact was output from the force plate in the form of Ground Reaction Force (GRF) with time. GRF is a measure of the load applied by the force plate as a reaction to the impact and is measured as three independent forces in the vertical and two perpendicular horizontal directions. Unlike human subjects who create both vertical and horizontal forces upon impact, the mechanical tests used for impacts in this investigation produce purely vertical forces, allowing the horizontal GRF measurements to be discarded. Further references to force throughout this chapter refer to the Vertical GRF (VGRF) produced by the impact of a mass onto a shockpad or shockpad-carpet system.

VGRF data was sampled at a rate of 12 kHz. Such high sampling rates produced an excess of data in terms of describing the force-time behaviour during the impact. However, the high sampling rates were shown to be necessary in preliminary testing as it reduced errors produced from the integration of the force-time data to calculate velocity and deflection of the shockpad.

VGRF-time data was measured for two different mass types impacting a range of shockpads and shockpad-carpet systems. A hockey ball was used to record the behaviour of ball impacts and a Clegg Hammer used to simulate player interactions. The hockey ball was selected as it provided a rigid mass with fewer variables than other inflatable ball types and also allowed a direct comparison with results from the mechanical testing conducted in Chapter 4. A spring contained in the Berlin Artificial Athlete complicated data collection as impact velocity and equivalent mass of the impactor were difficult to calculate. The Clegg Hammer was therefore used as an alternative to the Berlin Artificial Athlete to simulate player interactions. The characteristics of the hockey ball and Clegg Hammer are given in Table 5.1.

5.2.3 Mechanical Impact Method

The hockey ball was dropped manually from a height of 1.5 m measured against a surveying staff. The staff was placed on the floor behind the force plate to prevent interference in results due to movement. The thickness of the shockpad was added to the 1.5 m drop height as the staff on the floor below the top surface of the shockpad. A board was fixed perpendicular to the staff with a 1.5 m drop height between the bottom of the ball and the upper surface of the shockpad, allowing the ball to be dropped accurately in the centre of the shockpad away from the staff. Five ball drops conducted in the centre of each shockpad and measurements taken by the force plate recorded by the interfaced computer.

Clegg Hammer tests are generally conducted by standing on the surrounds of the guidance tube when the mass is dropped to prevent movement. For these tests the sides of the guidance tube were held by one person while another dropped the mass, as it was not possible to stand on the sides of the guidance tube due to interference caused to the force plate readings. Five drops were conducted in the centre of each shockpad and readings from the force plate recorded.

Hockey ball and Clegg Hammer impacts were conducted three times on a benchmark shockpad and once on shockpads ranging from 8, 15 and 20 mm in thickness. The mix design for each shockpad is outlined in Table 4.5. The benchmark shockpad was tested three times to determine the reproducibility of the method in determining shockpad behaviour.

Thickness was shown to be the key mix design variable by mechanical testing in Chapter 4. The marked change in mechanical properties warranted further investigation of how thickness affects shockpad behaviour and how these changes may be described by a mechanical model. Shockpad samples 8, 15 and 20 mm in thickness, in addition to the 12 mm benchmark shockpads, produced a range of four shockpad thickness for investigation. Shockpad samples used in the mechanical testing in Chapter 4 were reused for shockpad behaviour testing as there were no visible signs of damage caused by previous testing, or changes in properties measured, and were deemed to provide less potential for behavioural changes than new shockpads constructed for the purposes of this testing programme.

In addition to ball and Clegg Hammer impacts on shockpads, the composite behaviour of shockpad and carpets were also tested to observe the effect of the carpet layer on impact behaviour. The same procedure for ball and Clegg Hammer impacts was followed as outlined for shockpad testing. Tests on shockpads of varying thickness (including testing on the benchmark shockpad) were repeated using the same generic water-based hockey carpet and 3rd generation carpet were used as for mechanical tests conducted in Chapter 4. Specifications are provided in Table 4.11.

The hockey carpet was tested dry due to issues with water evaporation and water distribution and also because it allowed comparison of shockpad behaviour with mechanical properties. Sand and rubber in-fill for the 3rd generation pitch were refreshed according to manufacturer specifications for the testing. The movement of in-fill during testing, particularly with the Clegg Hammer, required the carpet to be moved to a new position for each different shockpad. It may however produce some differences in results recorded for each successive impact on the same shockpad, but due to the loose nature of the in-fill material this was difficult to control.

In total, five Hockey ball and five Clegg Hammer impacts were recorded for three benchmark shockpads and three shockpads of varying thickness. These tests were repeated for two generic shockpad-carpet systems, again observing the effect of shockpad thickness. The large sampling time where data was collected by the force plate required the relevant data from each impact to be extracted and graphed. The large quantity of data from this testing programme was reduced by the selection of one Clegg Hammer and one ball impact from each shockpad and shockpad-carpet system that best represented the average force-time behaviour in terms of peak force and slope of loading and unloading from each group of five to be analysed further.

5.2.4 Force Plate Data Analysis

Force-time data collected from the force plate required further analysis to enable shockpad behaviour to be described in terms of deflection and energy losses and to put the data in a form that can be more easily modelled.

The analysis required a number of steps to be performed. Firstly, force-time data was filtered to remove noise created by the force plate. The filtered data was then integrated to determine shockpad velocity and integrated a second time to determine deflection. Finally, energy loss and return and also stress and strain were calculated from the resulting force-deflection data to create several parameters by which shockpad behaviour could be described and compared and also provided a form for the data that could be easily modelled. The steps performed to analyse the force-time data are given in the following sections.

5.2.4.1 Filtering

Force-time data collected from the force plate for ball and Clegg Hammer impacts with relatively long contact times contained a regular noise pattern in both loading and unloading behaviour that was not observed in impacts with shorter contact times. The raw force plate data shown in Figure 5.3 contains a regular noise pattern after large peak of the impact and is attributed to resonance in the force plate.

The natural frequency of the force plate was 850 Hz in the vertical direction. The additional mass of the shockpad placed on the force plate reduced the natural frequency according to Equation 5.1, where the value of mass is increased and stiffness remains constant. The frequency of the vibration was calculated to be approximately 800 Hz, confirming these vibrations were due to force plate resonance.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad \text{----------} \quad \text{Equation 5.1}$$

Where:

f_n	=	Natural Frequency	[Hz]
k	=	Stiffness	[N/m]
m	=	Mass	[kg]

The noise observed in impacts with relatively longer impact times was not useful in describing any aspect of the impact and hindered further data analysis. A Butterworth low pass filter was applied to all data to retain its form in terms of peak force and contact time, but smoothed the loading and unloading behaviour to remove unwanted noise. The filter acted to eliminate all noise with a frequency below a set cut-off point and was selected as it was shown in the literature review to be commonly used by biomechanics researchers to remove noise from force plate data.

The Butterworth low pass filter was applied using Matlab (Mathworks, Vers. 7.2) as shown by the script below. In Line 1, the force data series (f_0 to f_n) was input into the Matlab programme. In Line 2, the filter coefficients, a and b, are calculated from the type of filter (butter represents the Butterworth filter), p, the order of the filter and C_f, the cut-off frequency. Line 3 applies the filter by assigning a name for the series of filtered data (F_2) and instructs Matlab to use the coefficients a and b and the original force data set, F. The filtfilt command refers to the time domain of the filter. It applies the filter twice, once in the positive time direction and then backwards through the data to provide a zero time shift in the data.

Line 1: $F = [f_0 f_1 \ldots f_n];$

Line 2: $[b,a] = butter\,[p, w_n];$

Line 3: $F_2 = filtfilt\,(b, a, F)$

The low-pass Butterworth filter acted to remove noise by suppressing data with a frequency above the cut-off frequency. The w_n term input into Matlab is a number between 0 and 1, determined as a fraction of the Nyquist frequency and cut-off frequency (Intel, 2006). The Nyquist theory states that if data is sampled at a given frequency, then the data can only contain frequency components between zero and half the sampling frequency. The Nyquist frequency is given by Equation 5.2 using the 12 kHz sampling frequency. The value of w_n was determined from the Nyquist frequency (Equation 5.2) and trialling of a range of cut-off frequency that was able to remove noise from the data signal. The optimum cut-off frequency for removing noise was determined to be 390 Hz, providing a w_n value of 0.065.

$$f_{niq} = \frac{f_s}{2} \qquad \text{------- Equation 5.2}$$

$$w_n = \frac{f_c}{f_{niq}} \qquad \text{--------- Equation 5.3}$$

Where:

f_{niq}	=	Nyquist Frequency	[Hz]
f_s	=	Sampling Frequency	[Hz]
w_n	=	Matlab Low Pass Cut-off Point	-
f_c	=	Cut-off Frequency	[Hz]

The order of the filter, p, determines the sharpness of the cut-off point. A range of orders were tested on force date, shown in Figure 5.4, to find the order that produced the minimum level of distortion to the data. A second order filter was selected as the slope of loading and unloading followed the raw data more closely than higher order filters. However, the application of the filter twice to retain the same time domain had the same effect as applying a fourth order filter.

A comparison of raw data and data filtered with a second order Butterworth low pass filter with a cut off frequency of 0.065 (as a fraction of the Nyquist frequency) is shown in Figure 5.5. The filtfilt function ensured there was no change in the contact time of the impacts however a reduction in the peak force was observed for all filtered data that contained resonant frequency noise, whereas originally smooth data remained unchanged. Greater forces generated larger differences in the peak force between the filtered and unfiltered data. For Clegg Hammer impacts on 12 mm shockpads these differences were as large as 16%, but for the same impact on a 20 mm shockpad-3rd generation carpet system these differences were reduced to 0.5%. The difference of 16% reduced the peak force by 1000 N, which is significant in terms of determining peak force for shockpad behaviour. However, noise created by force plate resonance was observed to distort the raw data and hence to determine shockpad behaviour it was required to be smoothed to create a uniform and usable data set. Further analysis of force-time data to calculate velocity and deflection of the shockpad through integration greatly amplified the resonance and created difficulty in determining energy return and losses. Filtering was thus determined to be a necessary process despite any effect on the peak force recorded.

5.2.4.2 Displacement and Velocity

Force-displacement data is generally used by researchers to describe shockpad behaviour as it describes the parameters of maximum displacement, stiffness, energy loss and recovery. The filtered Vertical Ground Reaction Force (VGRF)-time output from the force plate was converted to vertical force-displacement data using a series of integrations.

The free body diagram for a mass impacting a shockpad is shown in Figure 5.6. Newton's Second Law of Motion states that the net force is given by the sum of the masses multiplied by their respective acceleration as shown in Equation 5.4. In the case of a body impacting a shockpad, there are two masses being accelerated towards the force plate, the ball (m_1) and the portion of the shockpad undergoing deformation (m_2) as shown by Equation 5.5.

$$\sum F = ma \quad \text{-------- Equation 5.4}$$

$$\sum F = m_1 a + m_2 a \quad \text{-------- Equation 5.5}$$

Where:

F	=	Force	[N]
m	=	Net Mass	[kg]
a	=	Acceleration	[m/sec^2]
m_1	=	Mass of Ball	[kg]
m_2	=	Mass of Shockpad	[kg]

The mass of the ball remains constant during the impact, however, the mass of the shockpad being accelerated towards the force plate increases with deformation as an increasing volume of shockpad is displaced in the direction of the force plate. Shockpad mass is the product of the volume of shockpad being deformed and shockpad bulk density. The shape of deformed shockpad is likely to be trapezoidal, similar in shape to deflection bulbs measured in impacts with soils. The volume of the complex-shaped trapezoid is difficult to predict accurately as the angle of its sides are not known and it will vary with deformation. An acceleration gradient would also exist across the trapezium at any time with areas directly below the ball undergoing greater accelerations than those deeper within the shockpad which may be at rest.

To quantify the maximum mass of shockpad undergoing acceleration, quasi-static compression testing was used to measure shockpad deflection under a 1200 N load, typical of that produced during a ball impact. A deflection of approximately 5 mm was measured. At 5 mm deflection, a hockey ball 71 mm in diameter would have an area 3.9×10^{-3} m^2 in contact with the shockpad (assuming the shockpad deforms around the ball). Assuming the shape of shockpad being deformed is a simple cylinder with a depth of 5 mm and area of 3.9×10^{-3} m^2, a volume of 1.9×10^{-5} m^3 is accelerated towards the force plate. The density of the benchmark shockpad was 550 kg/m^3 and using the product of volume and density, the approximate mass being accelerated towards the force plate is 11 grams.

The hockey ball used to conduct the impacts had a mass of 160 grams. The approximate maximum mass of shockpad undergoing deformation, 11 grams, is 7% of the ball's mass. When considering the number of parameters required to accurately calculate the mass of shockpad undergoing deformation at each time interval, the unavailability of equipment to measure it and at its maximum being only 7% of the ball's mass, shockpad mass was considered negligible. The overall effect however, would produce a slight reduction in acceleration data and therefore reduction in velocity and deflection measurements.

VGRF data was used to obtain acceleration data by transposing Equation 5.4 to give Equation 5.6. The mass of the ball was measured as 160 grams by taking the average of five readings taken on a digital mass balance. An acceleration-time graph was produced for each impact as shown in Figure 5.7 for ball impact with a benchmark shockpad.

$$a = \frac{F}{m} \quad \text{---------} \quad \text{Equation 5.6}$$

Acceleration-time data was integrated to obtain velocity-time data according to Equation 5.7. The first point of impact (t=0) was defined as when the VGRF reading was first greater than zero and the last point of contact (t=max) when VGRF returned to zero. As there was no equation to describe the acceleration-time behaviour of a shockpad, the integral was determined from an approximation of the area below the acceleration-time graph. The trapezoidal rule was used to divide the area below the curve into small segments as each time interval and approximate the line of the curve between each segment point to be linear. The cumulative trapezoidal area formed by the addition of each time segment and the linear curve section is given by Equation 5.8. Terms t_1 and t_2 refer to the time at the start and end of the time interval and a_1 and a_2 are their respective acceleration values. The term v_p refers to the sum of previous trapezoid areas (cumulative velocity). Differences produced by approximating the curve into straight line segments were reduced by using a high data sampling rate (12 kHz) and therefore increasing the number of segments over which the curve was linearised. The 12 kHz sampling rate provided one data sample per 0.08 msec, an example, the Clegg Hammer impact on the 12 mm shockpad provided 56 data points.

$$v = \int_{t=o}^{t=\max} a.dt \quad \text{---------} \quad \text{Equation 5.7}$$

$$v = \left[(t_2 - t_1) \times \left(\frac{a_1 + a_2}{2} \right) \right] + v_p \quad \text{---------} \quad \text{Equation 5.8}$$

Where:

v	=	Velocity	[m/sec]
a	=	Acceleration	[m/sec^2]
$t_{1,2}$	=	Time Period	[sec]
$a_{1,2}$	=	Acceleration Period	[m/sec^2]
v_p	=	Cumulative Velocity	[m/sec]

To calculate the initial velocity (at t=0) of the shockpad it was assumed that at the point of impact, the falling mass instantaneously imparted its velocity on the shockpad and the two objects remained in contact moving at the same velocity until the VGRF had returned to zero. Potential energy from the impactor, E_p, was converted into kinetic energy, E_k, used in deformation of the shockpad using Equation 5.11. Assuming there is no energy lost at the point of impact, the impact velocity was determined using Equation 5.12. This assumption of instantaneous velocity imparted by the falling mass onto the shockpad is not strictly correct for the initial stages of contact; however is a necessary approximation as actual velocity of the shockpad directly below the ball is difficult to measure accurately.

The resulting velocity-time graph is shown in Figure 5.8. Deflection-time data was obtained from this velocity-time data using the same trapezium method of approximating the area under a curve. Deflection (x) was calculated from the integral of velocity with respect to time as given by Equation 5.12. The trapezoidal rule for calculating the area below the velocity-time curve is given by Equation 5.13 where t_1 and t_2 are the time intervals for the beginning and the end of the segment and v_1 and v_2 are their respective velocities. The x_p term refers the sum of deflection for all previous segments (cumulative deflection). The initial deflection of the shockpad when first contact occurs is assumed to equal zero. A typical deflection-time graph for a ball impact with a shockpad is shown in Figure 5.9.

$$E_p = mgh \quad \text{---------} \quad \text{Equation 5.9}$$

$$E_k = \frac{1}{2}mv^2 \quad \text{----------} \quad \text{Equation 5.10}$$

$$mgh = \frac{1}{2}mv^2 \quad \text{----------} \quad \text{Equation 5.11}$$

$$v_i = \sqrt{2gh} \quad \text{----------} \quad \text{Equation 5.12}$$

Where:

E_p	=	Potential Energy	[J]
m	=	Mass	[kg]
g	=	Gravity	[m/sec^2]
h	=	Drop Height	[m]
E_k	=	Kinetic Energy	[J]
v_i	=	Impact Velocity	[m/sec]

VGRF-deflection data was obtained by plotting the deflection data obtained from the above calculations with the original filtered VGRF data. A typical VGRF-deflection graph is shown in Figure 5.10.

$$x = \int_{t=0}^{t=max} v.dt \quad \text{-------} \quad \text{Equation 5.12}$$

$$x = \left[(t_2 - t_1)\times\left(\frac{v_1+v_2}{2}\right)\right] + x_p \quad \text{----------} \quad \text{Equation 5.13}$$

Where:

x	=	Deflection	[m]
v	=	Velocity	[m/sec]
$t_{1,2}$	=	Time Period	[sec]
$v_{1,2}$	=	Velocity Period	[m/sec]
x_p	=	Cumulative Deflection	[m]

5.2.4.3 Energy Input, Return and Loss

The energy input into an impact is determined by the mass and drop height of the impactor. The amount that was lost during the impact and returned to the impactor is dependent on the behaviour of the shockpad being impacted. Figure 5.11 shows an example of the force-deflection behaviour of a ball impacting a shockpad. The review of literature showed the area contained below the loading curve of a force-deflection graph is a measure of the energy input into an impact, the area below the unloading curve is the energy returned and the area between the loading and unloading curves is a measure of the energy lost during the impact.

The area below the loading and unloading curves of each force-deflection graph was approximated using the trapezium rule. Energy input into deformation of the shockpad by the impactor was determined using Equation 5.14 and energy returned to the impactor by the shockpad given by Equation 5.15. Energy loss is the calculated from the difference of energy input to energy returned and is given by Equation 5.16.

$$E_i = \int_{x=0}^{x=max} F.dx = \left[(x_1 - x_2)\times\left(\frac{F_1 - F_2}{2}\right)\right] + E_p \quad \text{--------} \quad \text{Equation 5.14}$$

$$E_o = \int_{x=max}^{x=0} F.dx = \left[(x_1 - x_2)\times\left(\frac{F_1 - F_2}{2}\right)\right] + E_p \quad \text{---------} \quad \text{Equation 5.15}$$

$$E_l = E_i - E_r \quad \text{---------} \quad \text{Equation 5.16}$$

Where:

E_i	=	Energy Input	[J]
E_o	=	Energy Return	[J]
F	=	Vertical Force	[N]
$F_{1,2}$	=	Force Period	[N]
$x_{1,2}$	=	Deflection Period	[m]
E_p	=	Cumulative Energy	[J]

5.2.4.4 Stress and Strain

Force-deflection of shockpads and shockpad-carpet systems were converted to stress-strain behaviour to observe the effect of normalising shockpad thickness. Force, F, was converted into stress, σ, using Equation 5.17. Contact area, A, was treated as a constant term of 1.96 x 10^{-3} m^2 for Clegg Hammer impacts due to the flat face of the mass and the assumption of negligible edge effects. The spherical nature of the hockey ball meant contact area between the ball and shockpad varied with deflection of the shockpad. It was assumed the shockpad deformed to conform to the shape of the rigid ball during the impact as shown in Figure 5.12. The contact area, A, for ball impacts is given by Equation 5.18.

$$\sigma = \frac{F}{A} \quad \text{---------- Equation 5.17}$$

$$A = 2\pi \times x\sqrt{2rx - x^2} \times \sqrt{\frac{r^2}{2rx - x^2}} \quad \text{--------- Equation 5.18}$$

Where:

σ	=	Stress	[Pa]
F	=	Force	[N]
A	=	Contact Area	[m^2]
r	=	Ball Radius	[m]
x	=	Deflection	[m]

Strain, ε, (expressed as a percentage) of shockpads and shockpad-carpet systems was determined using Equation 5.19 where t is the thickness of the shockpad and x_o and x_f are the initial and final deflections of the shockpad, as shown in Figure 5.13. For these initial stages of investigation into the combined behaviour of shockpad and carpet systems, the shockpad and carpet are assumed were assumed to be a single element with the same properties. The thickness of shockpad-carpet systems was determined from the total combined thickness of shockpad and carpet pile height.

$$\varepsilon = \left(\frac{x_f - x_o}{t}\right) \times 100 \quad \text{---------- Equation 5.19}$$

Where:

ε	=	Strain	[%]
x_o	=	Initial Deflection	[m]
x_f	=	Final Deflection	[m]
t	=	Thickness	[m]

5.2.4.5 Average Stiffness

Using a visual method to compare force-deflection behaviour of shockpads was subjective. Observing the behaviour of one shockpad on a set scale and then comparing it to the force-deflection behaviour of a second shockpad on a different scale altered the extent of non-linearity. A measurement of non-linearity was required to accurately compare the behaviour of different shockpads and quantify the extent of variations. Since shockpad stiffness was a measure of the gradient of the force-deflection behaviour, changes in stiffness between the initial stages and the final stages of compression provided a measurement of non-linearity.

Three distinct phases of shockpad behaviour were identified (detailed in the results); low stiffness, transition and high stiffness. These three phases represented the initial, intermediate and final stages of compressive behaviour, however the points of transition between one phase and the next were not well defined from a visual assessment. A method was devised using calculations of rate of change of stiffness as the initial stiffness and final stages were close to being linear, and the intermediate transition phase showed a more pronounced rate of change of stiffness.

The stiffness of each shockpad was determined for each deformation interval (i to i+1) using Equation 5.20. Plotting stiffness against shockpad deflection produced a curved graph similar to force-deflection behaviour and no discernable points of transition could be identified. The rate of change of stiffness for each was determined using Equation 5.21 which identified points where there were discernable points of change in behaviour and transition points could be identified.

$$k_i = \frac{F_{i+1} - F_i}{x_{i+1} - x_i} \quad \text{-------- Equation 5.20}$$

$$\frac{dk}{dt}=\frac{k_{i+1}-k_i}{t_{i+1}-t_i} \quad \text{-------- Equation 5.21}$$

Where:

k_i = Stiffness [$N.m^{-1}$]

F_i = Force [N]

x_i = Deflection [m]

t_i = Time [sec]

Force-deflection behaviour for Clegg Hammer impact on a benchmark shockpad is compared to the rate of change of stiffness-deflection graph in Figure 5.14. There are three distinct phases of behaviour, where initially in the low stiffness area there are small changes in stiffness until a point is reached where there is a marked change in rate of change of stiffness. This point was identified as the *transition point*. There is a near linear increase in rate of change of stiffness until a second marked change in rate of change in stiffness occurs and again a second transition point is reached.

In performing the analysis, some shockpads showed regions of little change in rate of change of stiffness during the later stages of the transition period and then sharply increased in rate of change of stiffness for a second period. This region was included in the transition period delaying the onset of the high stiffness phase of behaviour.

The average stiffness was determined for the initial and final phases of behaviour. Linear lines connected the origin, transition points and peak force to show average force-deflection behaviour for each phase. The gradient of the line for each phase of behaviour represented average stiffness. The average stiffness during the transition phase was not calculated because the high rate of change of stiffness during this phase meant it did not accurately represent the stiffness at any one point.

5.2.5 Procedure Validation Methods

Data filtering, making assumptions and approximating integrals produced some errors in obtaining velocity and deflection values from data collected from the force plate. In order to verify the method used to obtain these velocity and deflection values and to estimate the extent of errors, at least one independent test was required to be conducted alongside each impact for comparison.

Accelerometers were shown in the literature review to be commonly used by biomechanics researchers to verify force plate data. In the case of the hockey ball, an accelerometer attached to the shell would produce an uneven weight distribution, causing the ball to spin after release. Placing an accelerometer inside the ball may have weakened the rigid ball's integrity. For these reasons, the use of an accelerometer was discarded in favour of using a high speed camera to record the motion of the ball.

The high speed camera was able to capture images throughout the impact of a ball with a shockpad or shockpad-carpet system and be used to digitally measure deflection-time behaviour. This deflection-time behaviour measured by the camera was able to the directly compared with deflection-time behaviour derived from the force plate to verify the method of force plate data analysis. An additional test involving measurement of the ball's rebound height using a second digital (not high speed) camera provided a secondary source of verification for rebound height derived from force plate data.

The opaque tube of the Clegg Hammer prevented high speed camera measurements and rebound heights being used as a method for verification of force plate data. Instead, the Clegg Hammer's internal accelerometer was used for direct comparison with acceleration measurements derived from force plate data. The verification methods are outlined in detail in the following sections.

5.2.5.1 High Speed Camera Deflection Measurements

The principal method used to verify force-plate measurements for ball impacts was by measuring deflection throughout the duration of impacts using images taken with a high speed camera. The method used to obtain these images and analyse them is outlined in the following section together with a description of incurred errors and how they were minimised.

Method

A Phantom High Speed Camera was placed in line with the upper surface of the shockpad to avoid parallax errors. An area of 512 by 256 pixels was selected as the image capture area as it allowed the travel of the ball prior and post impact to be viewed in addition to the full range of the impact of the ball with the shockpad. Minimising image capture area to view the impact alone allowed higher image sampling rates, however, a larger area was selected to contain a full image of the ball prior to the impact to provide a scale to calibrate the deflection measurements.

Lighting was placed around the test area to provide the highest frequency of frame capture available. A rate of 2100 frames per second was the highest achievable where the white ball could be easily distinguished from the black background. Black markers for digitising points on the ball to measure deflection were made in random lines of dimples across the ball to ensure at least three markers would be distinguishable irrespective of ball orientation during impact.

Images of each impact of the hockey ball with the shockpad and shockpad-carpet systems were analysed using Phantom Software (Vision Research Inc, Vers. 7.0). An example an image captured during the impact is shown in Figure 5.15. A full image of the ball prior to impact was used as a scale to calibrate deflection. The distance from the leftmost point of the ball to the rightmost point of the ball was assigned to equal 70.8 mm (taken from an average of five measurements). The accuracy of these measurements was increased by ensuring the y-coordinates for the two points were equal to one decimal place, therefore ensuring the measurement was only in the x direction.

The force plate and camera were not able to trigger simultaneously, thus requiring the video frame where first point of contact between the shockpad and the ball occurred to be selected visually. This frame was set as the origin for time and displacement. For images where the first contact occurred between frames, the frame closest to showing the point of impact was selected and produced deflection measurement errors.

Three black marker points closest to the centre of the ball were selected for digitising each impact. In the digitising software, the crosshair was lined up with the centre of each marker point and when selected produced a white dot which was approximately some same size as the black marker. The digitised point was deemed accurate if the white dot covered the marker and minimal black could be seen surrounding it. The programme automatically progressed through each image after three points were selected and recorded the x and y coordinates for each point together with a time reference for the frame.

The y-coordinate (vertical coordinate) of the two dimensional image was used to measure vertical displacement, with change in y-coordinate equal to deflection, and the x-coordinate used to measure the accuracy of the method. Vertical displacement was obtained from an average of the y-coordinates for the three markers on each image and normalised against the y-coordinate from the first image. The time corresponding to each increment of displacement was obtained from normalising the time given for each frame against the time of the first impact.

Error Estimation

The initial contact between the ball and shockpad did not always coincide with a high speed camera image being recorded. Assigning the reference point of zero deflection to the image closest to actual point of impact produces some difference in deflection measurements taken for the purposes of data verification.

Images were recorded at a rate of 2100 frames per second. The velocity of the hockey ball falling from a height of 1.5 m was calculated to be 5.42 m/sec at impact. Between frames, a ball falling at 5.42m/sec would travel a distance of 2.58 mm. The greatest difference was incurred for impacts where actual impact occurred precisely halfway between images, where an difference of ± 1.29 mm in deflection measurements would occur. Shockpads with a benchmark mix design had a maximum deflection of around 6 mm, producing a maximum of 20% difference in deflection measurements. This difference is significant in terms of accurately verifying deflections obtained from force plate data, but a necessary compromise with image quality produced by using faster frame speeds and were minimised by taking images from three impacts for each shockpad and selecting the impact where contact is closest to an image being recorded.

A secondary source of difference was produced by manual digitisation of points on the ball throughout the impact to record deflection measurements. The digitised points were dimples of the hockey ball marked in black and were approximately 2 mm in diameter. At a magnification of three times the original image size, the cross-hair was aligned visually with the centre of the dimple and when selected a white marker appeared over the dimple. The marker was approximately the same size as the dimple so complete cover of the black marker ensured accurate digitising. The process of selecting three markers for digitising throughout each impact provided an average value for deflection. A standard error in average deformation recorded for each image of less than 10% was deemed satisfactory. Small amounts of spin produced by the manual ball dropping method accounted for this difference. The repeatability of the digitising method was measured by repeating the same process three times for each ball impact on a benchmark shockpad. The results in Figure 5.16 show the method to be repeatable, with deflection-time graphs for all three analyses following a similar line. The maximum deflections recorded range from 5.67 to 5.82 mm with difference of 1.4% from the average.

The two sources of error produced in the analysis of high speed camera images may accumulate if sets of images where impacts occur between frames are also poorly digitised. Conducting multiple impacts allowed selection of an image where the ball can be clearly seen and the occurrence of a frame matches the time of impact which reduced the potential for errors.

5.2.5.2 Ball Rebound Height Measurements

A secondary method to verify data obtained from the ball impacts was through a comparison of measured and calculated ball rebound height measurements. Ball rebound heights were measured using a digital video camera at 50 frames per second. A surveying staff with 1 cm gradations was used in the background of each impact to provide a marker in the background to measure rebound height against. Video footage was transferred to DVD and analysed using Windows Media Player

(Microsoft, Vers. 10). The programme was selected as it could play the footage back at a slow frame rate and pause at the peak rebound height. The rate of ball movement compared to frame rate of the camera was fast making the ball blurred for much of the rebound. However, as it approached peak height, the ball velocity slowed and at the peak height was zero. The ball image became focused at the maximum rebound height (zero velocity) allowing the distance to be measured against the surveying staff accurately. As the surveying staff measured in 1 cm gradations, the ball rebound height was measured to the nearest centimetre and produced an error of ± 0.5 cm. Parallax errors were reduced by positioning the camera image area over a 10 cm region of the expected rebound height determined from three preliminary test drops.

Ball rebound heights were predicted from force plate data. When the force acting on the shockpad returned to zero after unloading, it was assumed that the ball decoupled from the shockpad and was moving at the same velocity as the shockpad. This assumption does not regard the inertial effects of shockpad movement during unloading, however these were determined in Section 5.2.4 to be negligible due to the self-weight of the shockpad. The initial velocity of the ball is termed 'rebound velocity' and is equal to the velocity of the shockpad when force equals zero. The vertical ball rebound height was determined by using the rebound velocity in Equation 5.22. The calculated ball rebound heights were compared to the ball rebound heights measured using a digital video camera.

$$h = \frac{v_r^2}{2g} \qquad \text{----------- Equation 5.22}$$

Where:

h	=	Rebound Height	[m]
v_r	=	Rebound Velocity	[m/sec]
g	=	Gravity	[m/sec^2]

5.2.5.3 Clegg Hammer Peak Deceleration Measurements

The solid Clegg Hammer guidance tube prevented the use of high speed camera defection measurements and digital video camera rebound height measurements to verify force plate measurements for Clegg Hammer impacts. The best option available to validate force plate data for Clegg Hammer impacts was to compare peak deceleration measured through an accelerometer contained in the Clegg Hammer with acceleration data calculated from force plate data. This verification method was limited in that it could not verify the force plate displacement calculations, but did provide an accurate method for data validation. The main source of difference between the two sets of acceleration data was identified as the filters used to remove noise from the data. The filter used by the Clegg Hammer is not specified in literature and therefore could not be compared to the filter used for force plate data.

Peak deceleration data was output from the Clegg Hammer in units of gravity (g's). Multiplying readings by gravity (9.81 m/sec^2) allowed peak deceleration measurements to be directly compared with acceleration data derived from force plate readings.

5.2.6 Mechanical Modelling

A basic mechanical model was selected over a more complex numerical model as it presented the logical first step in determining an equation to describe the behaviour of shockpads. A thorough literature search found two researchers who had previously attempted to model the behaviour of shockpads specifically. Kim (1997) used a numerical model that failed to describe the non-linear and hysteretic behaviour characteristic of shockpads as it described linear points during loading and was unable to describe unloading behaviour. McCullough et al (1985) tested a series of mechanical models on foam materials suitable for use as shockpads. The foam shockpads were constructed from distinctly different constituent materials to the cast in-situ rubber shockpads, and therefore the model coefficients were not suitable, however, they did exhibit a similar non-linear and hysteretic behaviour.

The final model presented by McCullough et al (1985) contained a non-linear spring which was described by its stiffness and a non-linearity coefficient and a damping term. The non-linearity coefficient was given a constant value of 2 to describe all shockpads. It was shown by Shorten and Himmelsbach (2002) that using a variable value of the non-linearity coefficient was more accurate in describing synthetic sports pitches, and it was therefore anticipated that it may also be used to describe shockpads also. The model presented by Shorten and Himmelsbach (2002) was limited in its ability to describe shockpads as it did not contain the damping term which McCullough et al (1985) identified as being crucial in describing shockpad behaviour. The models of both McCullough et al (1985) and Shorten and Himmelsbach (2002) did not present a model suitable for describing shockpad behaviour but did provide a good basis for the development of one.

A series of steps, similar to McCullough (1985), were undertaken to determine the simplest mechanical model available to describe the non-linear and hysteretic behaviour of these cast in-situ rubber shockpads. The models ranged from a basic linear model consisting of one spring to a more complex non-linear damped model containing a parallel non-linear spring with a damper which combined the models of McCullough et al (1985) and Shorten and Himmelsbach (2002). A stress-stress strain model was also developed to for comparison to force-deflection models and both were evaluated in terms of their ability to describe shockpad behaviour. The development of suitable mechanical models and the methods used to optimise their fit to force plate data are detailed in the following sections.

5.2.6.1 Models

The principles of mechanical models were identified in the literature review. They were shown to consist of a parallel combination of springs and dampers, that were able to describe the elastic (linear) and viscous (damping) components of rubber and rubber-like material behaviour.

A series of models was used to develop the most accurate method of mathematically describing shockpad behaviour using mechanical elements. The first mechanical model used an elastic spring to describe shockpad behaviour and this model was developed into more complex models by the addition of dampers and non-linear springs. The development of the mechanical models is shown pictorially in Figure 5.17. The original model is termed the 'linear model' as it contains only a linear spring to describe behaviour. A damper is added in parallel to the spring to form a linear damped model, which shares the same form as the Kelvin-Voight model identified in the literature which is commonly used to describe rubber. The third model replaces the linear spring with a non-linear spring. It is termed the 'non-linear model' and is the same as the model presented by Shorten and Himmelsbach (2002). The final force-deflection model incorporates a damper with the non-linear model and is termed the 'non-liner damped model'. An additional stress-strain model was developed to model the stress of the impact for a given strain of the shockpad and strain rate of the damper.

The equations for the five models are described by Equations 5.23 to 5.27 provided in Section 5.4.1. The coefficients for each model were optimised (described in Section 5.2.6.2) to provide a best fit to the force-displacement and stress-strain values calculated from force plate data. The correlation between the optimised model and force plate data was used to evaluate the accuracy of the model in describing shockpad behaviour and the effect of thickness. The model deemed to most accurately describe shockpad behaviour was also applied to shockpad-carpet system data to determine the ability of the model to describe composite pitch behaviour.

5.2.6.2 Coefficient Optimisation

The coefficients for each model were optimised to give the best fit of the model to the force plate data that was possible. There was no software package readily available capable of determining the non-linear multivariate equation of the non-linear damped model. Matlab (Version 7.2) contained a Curve Fitting Toolbox that provided a simple method of inputting the equation and optimised coefficients were output. Initial and boundary conditions were determined by the programme; however the number of iterations and level of convergence could be manually altered. The Curve Fitting Toolbox was not capable to performing multivariate analysis and therefore the models with dampers, which also depended on the velocity of shockpad movement, could not be analysed.

In the absence of a suitable software package to solve the multivariate equations of the damped models, a programme was written in Matlab (Mathworks, Vers. 7.2). The equation in the programme could be altered to describe each model and required inputs of displacement and velocity data and initial values and boundary conditions for model coefficients. The programme output model coefficients that best described the force plate data and a measure of Root Mean Square Error (RMSE) to quantify the correlation between the model and the data. RMSE is a measure of the quadratic mean of the difference between values of the force plate data and the model. The values were squared and square rooted (to prevent positive and negative values cancelling each other out) to provided an overall measure of how far the model deviates from the force plate data and has the units of force (or stress). Models of force and stress were being compared and as RMS was had the units of force or stress, the errors for stress models appeared significantly larger than force. The RMS values were normalised against the value of peak force or stress for each model to provide a percentage error which were able to be compared.

The Matlab program was selected to analyse all models to ensure consistency of the output. The equations for each model were input into the program with initial and boundary conditions for each coefficient. The initial conditions were determined by manually altering coefficients to determine a visual best fit of the model to the force plate data. Boundary conditions were determined from limits of each coefficient. Stiffening of the shockpad upon loading required the non-linearity coefficient to be greater than one, while to provide damping, the damping coefficient was required to be greater than zero. All other boundaries were determined from an iterative process that reduced errors output by a model. Number of iterations and levels of convergence were input into the Matlab programme to ensure model coefficients were optimised. A trial and error process determined an appropriate level of iterations to be 120000. A level of convergence of 0.00001 was also used to stop the iterations early if further iterations were not producing a useful difference to the results.

5.3 Shockpad Behaviour

5.3.1 Introduction

The following section outlines shockpad and shockpad-carpet system behaviour determined from force plate measurements. The results of force plate measurements for Clegg Hammer and hockey ball impact testing on shockpads varying in thickness and for whole pitch systems are described in separate sections. Further results validating force plate measurements against independent tests are also described. A separate section discussing the results and their implications is also provided.

5.3.2 Benchmark Shockpad Behaviour

The compressive behaviour of shockpads resulting from impacts of a hockey ball and Clegg Hammer exhibited the same characteristics as the quasi-static compressively loaded shockpads presented in the literature review. Force-deflection behaviour of a benchmark shockpad impacted with a hockey ball, Figure 5.18, shows the same trend of a non-linear stiffness during loading and unloading as that presented by Walker (1996). Hysteresis, produced by the shockpad following different loading and unloading paths due to energy losses, was also exhibited by the shockpad tested by Walker (1996) and is exhibited by the ball impact together with a temporary compression set of the shockpad due the viscous nature of shockpads.

The force-deflection behaviour of a benchmark shockpad in response to hockey ball and Clegg Hammer impacts is shown in Figure 5.19. The two impactors differ in mass, shape and drop height and therefore produce different force-deflection behaviour. Energy inputs, returns and losses for the two different impactors are given in Table 5.2. The energy input into the shockpad by the Clegg Hammer is over four times that of a hockey ball impact; however both had 38% of their input energy returned, suggesting energy return is dependent on the properties of the shockpad not the impactor. The larger input energy of the Clegg Hammer produced a 5000 N impact force, compared to the 1300 N impact from a ball, however both produced similar maximum deflections which were calculated from force plate data.

The shockpad stiffened rapidly when impacted with the Clegg Hammer compared to the ball rebound. At around 1000 N, the curve steepens and becomes more vertical. The impact force exerted by the shockpad increases rapidly with minimal further deformation. The Clegg Hammer was used to simulate the foot of a player striking the shockpad. Stiffer shockpads clearly generate larger impact forces for players, which have been proposed by some researchers to cause injuries. The ball impact shows similar non-linear behaviour to the Clegg Hammer impact, but the gradient of the line demonstrates the shockpad could accommodate further deformation before stiffening and producing high impact forces.

There were three phases of behaviour observed in the loading section for both ball and Clegg Hammer impacts. These phases of behaviour are identified as low stiffness, transition and high stiffness behaviour. These three phases of behaviour and a physical description of the mechanics of each phase are described in further detail in the discussion of shockpad behaviour (Section 5.3.6).

5.3.3 Effect of Thickness

Force-deflection behaviour of the hockey ball impact for shockpads ranging in thickness from 8 to 20 mm is shown in Figure 5.20. A reduction in peak impact force of 1100 N was achieved by varying shockpad thickness from 8 mm to 20 mm, together with an increase in peak deflection of 2.2 mm. The initial average stiffness of shockpads ranged from 102 kN/m (8 mm shockpad) to 69 kN/m (20 mm shockpad). All of the shockpads reached the transition point (between high and low stiffness) at approximately 2.2 mm deflection, indicating the transition point may be independent of shockpad thickness. However, the average stiffness of the shockpad during and post transition increases with decreasing shockpad thickness. The final average stiffness of the 8 mm shockpad showed a 915% increase from the initial stages, while the 20 mm shockpad showed a 184% stiffness increase. These results show thinner shockpads to be more non-linear than thicker shockpads.

Overall, it was shown that peak forces and average initial and final stiffness reduced and peak deflections increased with increasing shockpad thickness. However, energy losses and returns are the most important aspect of a shockpad's behavioural response to a ball impact as it will dictate the ball's rebound height. The average energy return and loss for a ball impact on shockpads varying in thickness are given in Table 5.2. The results show no significant change in energy return when shockpad thickness is varied, indicting there is also no change in ball rebound height.

The Clegg Hammer impact was used to simulate the force-deflection behaviour of a shockpad in response to a player's heel strike. This force-deflection behaviour for a

Clegg Hammer impact with shockpads ranging in thickness from 12 to 20 mm is shown in Figure 5.21. No data was collected for the impact of a Clegg Hammer with an 8 mm shockpad as during preliminary testing the deceleration readings output by the accelerometer on the Clegg Hammer showed an overload and there was also a potential risk of causing damage to the force plate.

The peak force generated by the Clegg Hammer impact was reduced from 4900 to 2700 N by increasing the shockpad from 12 mm to 20 mm in thickness. This equates to a 45% reduction in peak force returned to a player which relates to increased shock absorbance for players, however it also produces a 66% increase in peak deflection which may produce fatigue in players. Average shockpad stiffness in the initial stages of deflection ranged from 356 kN/m (12 mm shockpad) to 238 kN/m (20 mm shockpad). The same transition point of approximately 1.7 mm is shared by shockpads of all thicknesses, earlier than the hockey ball impact but confirming that transition point does not alter with shockpad thickness. There was a 449% increase in average stiffness from initial to final stages of loading for the 12 mm shockpad, while the 20 mm shockpad displayed a more linear behaviour increasing in stiffness by 238%.

The proportion of energy returned to the Clegg Hammer for impacts with the shockpads of varying thickness, given in Table 5.2, shows an increasing energy return with increasing shockpad thickness. The reduction in energy losses may be explained by the different dynamics of behaviour exhibited by thin, highly strained shockpads which transfer significant amounts of force to the rigid force plate below. This phenomenon is explained in further detail in the discussion of shockpad behaviour (Section 5.3.6).

Force-deflection behaviour was converted to stress-strain behaviour to examine the effect of normalising thickness for ball and Clegg Hammer impacts. It was anticipated that normalising deflection may produce common loading and unloading behaviour for shockpads irrespective of thickness, changing only in terms of the peak stress reached.

The stress-strain behaviour for the hockey ball impact with shockpads of varying thickness is shown in Figure 5.22. There is no common behaviour shared by all shockpad thicknesses, particularly for the 8 and 12 mm shockpads, however, the thicker 15 and 20 mm shockpads do follow a similar load and unload path. A similar trend is shown as for the force-deflection behaviour of shockpads (Figure 5.20), where 8 and 12 mm shockpads show considerably sharper transitions and reach higher final stage stiffness than the thicker 15 and 20 mm shockpads. This difference in behaviour is attributed to the high modulus (and stiffness) reached by thinner shockpads, where the rigid force plate also begins to influence the measured behaviour.

In addition, some errors were produced in the resulting stress-strain graph due to the assumption of the shockpad deforming around the ball. The contact area was a function of deflection, and it was observed in the force-deflection behaviour that the shockpad significantly increased in stiffness towards the end of the loading phase particularly in the case of the 8 and 12 mm shockpads. A stiffer shockpad would be less accommodating to surrounding the ball and would therefore produce higher errors in stress calculations than for the more compliant 15 and 20 mm shockpads. Also, there may also be some deformation of the ball for shockpads where stiffness approached that of that of the rigid hockey ball. A more precise measurement of area may produce more accurate results and bring the behaviour of the thinner 8 and 12 mm shockpads more towards the load and unload path of thicker shockpads.

Calculations of area were more precise for determining the stress-strain behaviour of Clegg Hammer impacts for shockpads of varying thickness, as shown in Figure 5.23. The Clegg Hammer has a flat face in contact with the shockpad therefore producing a constant contact area throughout the impact duration. The thicker 15 and 20 mm shockpads follow the same load and unload path when the thickness is normalised by converting it to strain. The thinner 12 mm shockpad shows similar stress-strain behaviour but has some translation to the right. This behaviour may be best explained by the higher stiffness reached by the 12 mm shockpad than the thicker 15 and 20 mm shockpads, which shows a similar effect as for ball impacts.

5.3.4 Effect of Carpet Layer

This section examines the effect on overall behaviour of combining shockpad and carpet layers. The same two generic carpets were used as in Chapter 4; a water based hockey carpet with a short nylon pile and 3 mm integral shockpad and a long-pile 3rd generation football and pitch which was in-filled with rubber and sand. Both carpets were combined with shockpads ranging from 8 to 20 mm in thickness and were subjected to ball and Clegg Hammer impacts. The resulting behaviour is presented in the following sections.

5.3.4.1 Shockpad-Carpet System

A comparison of force-deflection behaviour of hockey ball impact on a benchmark shockpad and then in combination with the generic water-based hockey carpet and 3rd generation carpet above is shown in Figure 5.24. The introduction of the carpet layer is shown to reduce the impact force from 1170 N to approximately 600 N (similar peak force for both carpets), producing a 50% reduction in peak force. For both types of carpet-shockpad system there is an initial stage where the stiffness remains low and there is large deformation with minimal increase in force. The initial average stiffness of the shockpad alone was 95 kN/m, this was reduced to 22 kN/m for the water based carpet system and to 1 kN/m for the 3rd generation carpet system. This reduction is most likely attributed to deformation of the carpet pile and also the compaction of in-fill in the case of the 3rd generation carpet. The introduction of the carpet layers also reduced the average stiffness in the final stages of loading from 370 kN/m for the shockpad alone to 91 kN/m for the water based system and 87 kN/m for the 3rd generation system.

Similar reductions in the force-deflection behaviour are exhibited by the Clegg Hammer impact on the benchmark shockpad compared with the benchmark shockpad in combination with generic water based and 3rd generation carpets shown in Figure 5.25. Impact forces are reduced by approximately 50% through the introduction of these generic carpet layers. The initial average stiffness of the benchmark shockpad was 356 kN/m compared with 114 kN/m for the water based carpet system and 52 kN/m for the 3rd generation carpet system. The deflection where transition occurred was increased by the addition of the carpet layers from 1.7

mm for the shockpad alone to 2.5 and 3.2 mm for the water based and 3rd generation carpet systems respectively. The final average stiffness for the shockpad-carpet systems were 267 kN/m and 400 kN/m for the water based and 3rd generation systems respectively. These average stiffness calculations for the final stage of deformation for the shockpad-carpet systems presented a significant reduction in stiffness due to the carpet layer when compared with the 1600 kN/m final average stiffness for the shockpad alone. This increase in deflection to produce transition by the addition of carpet layers and reduced final average stiffness resulted in a system with reduced stiffness and peak impact forces during simulated player interactions.

A comparison of the energy input, return and loss for different shockpad-carpet systems is given Table 5.2. Higher amounts of energy loss are produced for shockpad-carpet systems than for the shockpad alone due to deformation of the carpet pile and compaction and displacement of the in-fill materials (approximately 10% difference). Both the ball and Clegg Hammer impacts on the 3rd generation carpet caused some of the rubber in-fill material to scatter from the carpet pile producing a noticeable loss. The scattering of in-fill material would cause a greater energy loss than if it were only compacted, and therefore could produce differences in the results due to uneven in-fill across the carpet. The errors were minimised by using a different section of carpet for each impact, and standard deviations for the 3rd generations carpet were comparable with the water based carpet which did not contain any in-fill.

5.3.4.2 Effect of Thickness

The effect of altering shockpad thickness for hockey ball impacts with shockpad-water based carpet systems and shockpad-3rd generation carpet systems are shown in Figure 5.26 and Figure 5.27 respectively. The 3rd generation carpet systems are grouped closely together, exhibiting little influence from the thickness of the shockpad layer below. Conversely, shockpad thickness is shown to influence force-deflection behaviour of water based carpet systems, where the graphs have a larger spread in terms of maximum deflection. These differences in behaviour are attributed to the thicker carpet pile and 40 mm depth of in-fill materials for the 3rd generation carpet which reduce the levels of force transmitted to the shockpad layer below compared to the shorter pile water based carpet.

Peak impact forces were reduced by 159N and 67N by the addition of a 20 mm shockpad below water based carpet and 3rd generation carpets respectively, demonstrating the addition of a shockpad layer does not significantly affect the behaviour of these carpets in terms of peak impact force. The initial average stiffness of the water based carpet alone was calculated to be 51 kN/m and this was reduced to 19 kN/m by the addition of a 20 mm shockpad and the final average stiffness was halved by the addition of a 20 mm shockpad below the water based carpet. There was less change in average stiffness for the 3rd generation system, where the addition of a 20 mm shockpad yielded no change in the stiffness during the final stage of loading.

The effect of altering shockpad thickness for Clegg Hammer impacts with shockpad-water based carpet systems and shockpad-3rd generation carpet systems are shown in Figure 5.28 and Figure 5.29 respectively. The higher energy impact of the Clegg Hammer, relative to the ball, shows more influence on system behaviour from the thickness of shockpad used in comparison to the hockey ball impact. The peak impact force was reduced by 49 to 58% by the use of shockpads ranging from 8 to 20 mm in thickness below the water based carpet. Peak impact force was reduced by 17 to 41% by using the same range of shockpads below the 3rd generation carpet. The initial average stiffness had less than a 5% reduction by altering shockpad thickness below the water based carpet, however the 3rd generation carpet stiffness was reduced by between 11 to 25% by using the 8 to 20 mm range of shockpads below the carpet. Deflection required to produce transition behaviour was unchanged by shockpad thickness in the water based carpet system, while the 1 mm delay in deflection to transition produced by the 20 mm shockpad-3rd generation carpet system was considered negligible when the total system thickness of 85 mm is considered.

Final average stiffness for the shockpad-carpet systems was shown to be significantly influenced by the use of a shockpad below both carpet layers. The water based carpet had a final average stiffness of 1341 kN/m with no shockpad layer and this was reduced to 740 kN/m by the introduction of an 8 mm shockpad and 186 kN/m for the 20 mm shockpad. The average stiffness for all other shockpad thicknesses fell within this range. A reduction in average stiffness by the introduction of shockpads to the 3^{rd} generation was also observed. The 878 kN/m final average stiffness was reduced within the range of 576 to 278 kN/m by the use of shockpads ranging in thickness from 8 to 20 mm.

The energy return of the shockpad-carpet system also plays an important role in ball rebound height and player performance. Table 5.2 shows that energy return increases with shockpad thickness for both the Clegg Hammer and hockey ball impacts for both carpet types, demonstrating impactor rebound height increases with shockpad thickness. The results measured in Chapter 4 showed ball rebound height was not influenced by shockpad thickness above 8 mm and ball rebound heights measured in this Chapter using a digital video camera (more detail in Section 5.3.5.2) showed the same trend. This difference between calculated energy return from force plate measurements and measured ball rebound heights may be accounted for by the calculation of energy return by the shockpad. Integration of force-deflection data amplifies errors produced by resonance of the force plate and the subsequent filtering. Thicker shockpads show more deflection recovery before the ball leaves the shockpad and therefore greater energy return, and as it was not possible to determine the actual point where the ball leaves the shockpad an assumption of returning to zero net force on the system was assumed. Actual measurements of time of ball and carpet dissociation would assist in a more accurate measurement of energy return. The rebound height of the Clegg Hammer was not able to be measured due to the opaque guidance tube.

The stress-strain behaviour of ball and Clegg Hammer impacts on water based carpet systems are shown Figure 5.30 and Figure 5.31 respectively. The hockey ball impact shows a linear loading where the elastic modulus is independent of shockpad thickness. The Clegg Hammer impact demonstrates a non-linear relationship between stress and strain and the maximum stress and strain reduces with shockpad thickness for both impacts. Similar to shockpad impacts, the 8 mm shockpad displays a higher final modulus than thicker shockpads for the Clegg Hammer impacts due to the force transferred to the foundation layer. This is not observed for the 8 mm shockpad for ball impacts as there is insufficient force transferred through the carpet and shockpad layers due to the lower energy of the impact.

5.3.5 Validating Force Plate Data

The following sections outline the results of validation procedures used to verify the force plate data. Ball impact measurements were verified by comparison to high speed camera deflection measurements and ball rebound height measurement recorded by an independent digital video camera. These measurements were not suitable for Clegg Hammer measurements therefore verification was conducted by a comparison of peak deceleration force plate measurements with decelerations measured by the Clegg Hammer itself.

5.3.5.1 Ball Deflection Measurements

Deflection-time behaviour of three ball impacts with the benchmark shockpad is compared for data taken from high speed camera (HSC) images and force plate data calculations in Figure 5.32. The HSC data displays a peak deflection of 5.7 mm compared with 5.9 mm predicted by the force plate, showing a good correlation between the two measurements, particularly as there is a lower sampling rate of the HSC images (almost 6 force plate data points for every one HSC image). The force plate measurements show the ball and shockpad decouple with 4 mm deflection of the shockpad remaining, whereas the HSC data suggests the shockpad returns its original state before the ball and shockpad decouple. HSC images, particularly the contrast between the shockpad and the lower half of the ball made it difficult to ascertain when shockpad decoupling actually occurred and therefore make comparison of the contact time for the two measurements difficult.

A difference of 1 msec in the time taken to reach peak deflection is shown to occur between the force plate data and HSC images. This difference is explained the method used to analyse both data sets. The unavailability of an automatic trigger to synchronise the HSC and force plate data required the zero time point to be manually determined. The zero time point was determined as the point of visual contact (from the frames) between the ball and shockpad for HSC measurements and the point where force values first increased for force plate data. If the two data sets were synchronised, a delay would be expected to occur between the time of first contact and the time this first contact was registered by the force plate due to the requirement of the stress waves to travel through the shockpad to reach the force plate, producing the time shift in the force plate data. This delay in measurement would produce a translation of the force plate data towards the right, aligning the peak deflections for force plate and HSC data images. However, for the purposes of verification of ball peak deflection a comparison between the two methods of measurement shown in Figure 5.33 corroborates the peak deflection values calculated from force plate data.

5.3.5.2 Ball Rebound Height Measurements

A comparison of ball rebound height measurements taken with a digital video camera with those predicted from force plate data is shown in Figure 5.34. Measured ball rebound heights fall within a small range (with large standard deviations), however, the predicted ball rebound height increases with shockpad thickness and little correlation is seen between the two data measurements.

There are numerous reasons that may account for the difference between measured and calculated rebound height measurements. The largest source of discrepancy results from initial assumptions made in the data analysis stage of force plate data calculations. Velocity calculations were conducted using the final velocity of the ball when vertical force returned to zero i.e. it was assumed to be the point were ball and shockpad were no longer in contact. The final stages of the impact for thicker shockpads were interfered with by resonance from the force plate and the selection for the point of zero impact was made by filtering the data including the first peak of resonance to smooth the line. Extrapolating the line of the force-time data to the origin and discarding the first peak of resonance would result in a higher velocity at decoupling and therefore a higher rebound height of the ball. A sample calculation of this for a ball rebound on a 15 mm shockpad (which required filtering due to the resonance) produced a 23 cm change in rebound height of the ball bringing it below measured ball rebound heights, which is considered significant. The extrapolation of data estimated the point of intercept with the origin, therefore, changes in the slope of the force-time graph disguised by the resonance are unknown. The filter also produced a significant shift of the final intercept to the right producing an underestimation in ball rebound height compared to the pre-filtered data and in addition, the integration required to calculate final velocity from force plate data magnifies the effect of resonance errors. The actual ball rebound height is therefore predicted to lie between those predicted by the two different methods which discard or smooth force plate resonance.

Further smaller errors may have resulted from some necessary assumptions made during data analysis. The point where the shockpad and ball were no longer in contact may have been earlier than zero net force assumed in these calculations and therefore the ball would have a higher velocity upon leaving the shockpad and therefore a higher rebound height. As the point of decoupling between the ball and shockpad could not be accurately measured using the high speed camera the extent is difficult to ascertain. Complete transfer of energy from the shockpad was assumed to also occur with no losses due to deformation in the ball which may also have affected the resulting final energy. The final stiffness of thinner shockpads was shown to be significantly higher than thicker shockpads, and therefore thinner shockpads have the more potential to produce deformation and energy losses in the ball, underestimating ball rebound height for thinner shockpads. The trajectory of the ball was also assumed to be straight in the upwards direction and any horizontal translation would reduce the ball rebound height measured by the video camera.

Earlier stages of data analysis such as selection of a point for the time origin of force-time data collected from the force plate results and the reduction in peak force caused by filtering also have the potential to affect acceleration, velocity and deflection calculations. The high degree of similarity between acceleration calculations derived from the force plate and Clegg Hammer measurements and also the peak deflection results from high speed camera compared to force plate data calculations suggests these earlier stages of data analysis did not affect the ball rebound height to the extent of the point selected as the final velocity.

The ball rebound height predicted by the force plate data was shown to be sensitive to the predicted final velocity of the ball. Further work in this area should consider how force plate resonance can be reduced or removed to measure the actual velocity of the ball upon decoupling with the shockpad. Further refinement of the assumptions of total energy transfer, levels of ball deformation and actual ball rebound trajectory would bring the measured and calculated ball rebound heights closer.

5.3.5.3 Clegg Hammer Peak Deceleration Measurements

A comparison of peak deceleration data output by the Clegg Hammer with peak decelerations calculated from force plate data is presented in Figure 5.35. The line of y = x shows there is an excellent relationship between the two sources of data, validating the data collected by the force plate for both shockpads and shockpad-carpet systems. Small error bars for both sets of data confirms a good relationship between Clegg Hammer readings and calculations derived from force plate data.

In all instances, with the exception of the 12 mm shockpad, the data lies just above the linear line showing slightly higher values for the acceleration data calculated from the force plate measurements. This may be due to the filter applied by the Clegg Hammer to peak deceleration readings prior to output reducing peak values further than the filter manually applied to the force plate data, however, as the details of the Clegg Hammer filter are not documented it cannot be confirmed. Assumptions made in the calculations of force plate data, such as negligible mass of the shockpad, may also account for these minimal deviations from a linear relationship between data.

5.3.6 Discussion of Shockpad Behaviour

This section of work discusses the results of shockpad behaviour testing. The discussion is divided into subheadings that examine characteristics of shockpad behaviour and explain this behaviour in terms of the physical mechanisms occurring at each stage of behaviour. An examination of the effect of shockpad thickness and carpet layer on the force-deflection and stress-strain behaviour of shockpads is also provided and the section is concluded with an examination of the quality of the force plate data collected and its ability to describe shockpad behaviour.

Characteristics of Shockpad Behaviour

Changes in the porous structure of the shockpad are shown schematically in Figure 5.18 for each stage of the force-deflection behaviour of a shockpad. Initially, the shockpad is easily deformed with the application of a small force. At this stage, the rubber particulate displaced from the surface during the impact can be easily accommodated in the matrix of compressible air voids and the shockpad remains very compliant. In the second stage, the stiffness response begins to rapidly increase as the percentage of air voids decrease. Rubber particulate can no longer be easily accommodated in the air voids and rubber to rubber contact points increase. With increasing force, the shockpad becomes much stiffer than in the initial stages of the impact. As the rubber itself undergoes significant deformation, the shockpad begins to behave more like a solid section of rubber.

During unloading, the ball begins to move in the upwards direction and the shockpad moves towards regaining its original shape. The shockpad is initially stiff as shown by the steep gradient of the force-deflection curve. The curve is again non-linear during unloading, decreasing in stiffness as the shockpad recovers. The dense shockpad regains air voids as rubber particulates are able to return to their original positions upon unloading. This recovery process occurs rapidly initially, but begins to slow as the deflection of the shockpad nears zero.

The energy input into the shockpad during the impact is given by the area below the loading section of the force-deflection graph. Potential energy from the falling ball or Clegg Hammer is converted into kinetic energy used in deforming the shockpad; therefore the area is dictated by the mass and drop height of the impactor not the properties of the shockpad. The effect of varying impactor energy through drop height was not considered within the scope of this project, but is known to have the effect of altering shockpad behaviour in terms of peak force and peak deflection, (Carré et al, 2004) Peak forces and deflections can also be altered by changing shockpad design, however the area below the graph remains constant for the same impactor mass and drop height. When maximum deflection is reached, the ball no longer has energy to deform the shockpad. Shockpads store potential energy through deformation which it returns to the impactor during unloading. The energy dissipating property of rubber is well documented in literature and as rubber is the major constituent of shockpads it is not surprising that energy is lost during impacts. The energy losses, and therefore the energy returned to the impactor, are dependent on shockpad design.

The three distinct phases of shockpad behaviour shown in Figure 5.18 were common to all shockpads in the range of 8 to 20 mm in thickness undergoing a compressive impact. Characteristics of each phase of shockpad behaviour are outlined below.

Phase One – Air Void Compression

This initial phase of shockpad behaviour is characterised by high amounts of deformation for small applied loads and therefore shockpad stiffness is relatively low compared to later phases of behaviour. Extensive deformation of the shockpad is facilitated by the shockpad structure containing 47% air voids (at a bulk density of 550 kg/m^3) which offer low resistance to closure by temporarily displaced rubber particles. In order for the rubber particles to displace, they must to overcome the binding force of the binder. The ease with rubber can overcome the binding force will be dependent on the shockpad binder content and the mechanical properties of the binder used.

Phase Two – Transition

This phase of behaviour is characterised by a transition from low to high shockpad stiffness. The relatively high rate of change of shockpad stiffness demonstrates where shockpad deformation changes from compression of air voids to compression of the rubber particles. Some compression of smaller air voids and initial stages of rubber particle compression will occur. The area below the loading curve is dictated by the input energy of the impact and therefore the increase in shockpad stiffness produced during the transition phase reduces deformation to maintaining a constant area higher impact forces result.

Phase Three – Rubber Compression

This phase of behaviour is characterised by small deformations for high applied loads and therefore shockpad stiffness in relatively high compared to earlier phases of behaviour. There is greatly increased rubber to rubber contact and internal friction of the binder, rubber stiffness and the effect of the binder coating must be overcome for compression of rubber particles. Some compressive deformation of the rubber particles and the binder will occur and the shockpad will begin to behave more like a solid section of rubber. The stiffness reached during this phase of behaviour will be dependent on the mechanical properties of the rubber and binder and the thickness of the binder coating.

Each of the above phases describes the behaviour of the shockpad matrix during deformation, however, in reality a shockpad is most likely experiencing a combination of all three phases simultaneously across its cross section. The actual behaviour of a shockpad under a dynamic compressive impact is a complex process. Stress waves from the impact travel through the shockpad and larger air voids are easily compressed in the area immediately in contact with the impactor and the stiffness of the shockpad remains low. As the load in increased, the deformation will become more localised and create a stiffness gradient across the thickness of the shockpad. Areas directly in contact with the impactor may transition and reach the third phase of behaviour while areas several millimetres below the surface may be just beginning the first phase of behaviour. When considering the shockpad in three dimensions, a similar strain gradient would exist across the width of the shockpad.

The hockey ball is spherical and the Clegg Hammer flat in shape and so each impactor would create distinctly different deformation behaviour of the shockpad locally. All points of the Clegg Hammer come into contact with the shockpad simultaneously as the Hammer has a flat surface. The behaviour of the shockpad is uniform below the hammer, with a deflection gradient existing across the thickness of the shockpad. The hockey ball is spherical making localised deflection more complex. Deflection of the ball is measured from the first point to contact the shockpad and therefore the point of the ball producing largest deflection of the shockpad. Other points of the ball also come into contact with the shockpad as deflection increases, however the deflection of these points is not uniform across the section of ball in contact with the shockpad. A deflection gradient would exist across the thickness of the shockpad, in the radial direction emanating from the ball. The shape of the ball also produces a shearing action in the shockpad during impact and therefore introduces a tensile force component, whereas the Clegg Hammer impact is predominantly compressive.

While in reality shockpad behaviour is clearly somewhat complex, the ability to identify and explain general phases of behaviour during loading and unloading provides a method to compare shockpads, observe changes in behaviour and indicate the most likely method to develop a suitable model to predict this behaviour. Determining the force-deflection behaviour of shockpads and classifying the loading portion of this into the three phases of behaviour quantified characteristics that allowed changes in behaviour to be measured. These characteristics were average stiffness for each phase and deflection required to reach the transition point. Combining these characteristics with peak force, peak deflection and energy return provided numerous characteristics of shockpad behaviour to identify and quantify changes.

Effect of Shockpad Thickness

Shockpad thickness was shown to affect peak impact forces, peak deflection, initial average stiffness and final average stiffness, however the deflection required to reach the transition phase (Phase 2) was the same for both impactors. Significant reductions in peak impact force were achieved by varying shockpad thickness from 8 to 20 mm (12 to 20 mm for Clegg Hammer impacts). The area below the loading section of the force-deflection curve was controlled by the potential energy of the impactor transferred to the shockpad and was therefore constant for each impactor type. Thicker shockpads retained a low stiffness state (Phase 1) for greater deformation than thinner shockpads, and to maintain constant area below the force-deflection graph, peak impact forces were reduced.

Both peak impact force and stiffness (rate of change of loading) of sports surfaces have been associated with player injuries and are therefore important characteristics of shockpad behaviour to measure. Comparing the average stiffness for each of the three phases provided a means of measuring changes in shockpad behaviour. The initial and final phases of behaviour were near linear and therefore the average stiffness provides an accurate measure of changes in the rate of change of loading.

Thinner shockpads, particularly the 8 mm shockpad, showed a large increase in initial and final stiffness during loading and peak impact force. This high stiffness occurred after transition, where only small amounts of additional deformation can be produced by the shockpad. The force which cannot be attenuated within the shockpad is transferred to the rigid force plate located below the shockpad and the behaviour measured becomes a composite behaviour of the shockpad and force plate. Thicker shockpads (and the addition of carpet layers) are able to increasingly attenuate the force within the shockpad and therefore transfer increasingly small forces to the force plate below and therefore the behaviour of the force plate becomes less apparent. This effect is seen, for example, in Figure 5.23, where the thinner 12 mm shockpad shows a higher modulus than the thicker 15 and 20 mm shockpads.

The deflection required to reach the transition phase was not altered by shockpad thickness, but was reduced for Clegg Hammer impacts compared to hockey ball impacts. This reduction in transition deflection is expected for the higher energy Clegg Hammer impact due to the higher rate of loading it produces. Extending the deflection required to reach the transition phase was dependent on the air voids available for deformation. As the air void proportion was constant in all shockpads, there was no change in deflection required to reach this point. It is anticipated deflection may be extended by decreasing the bulk density (increasing air void content), offsetting the transition point and allowing the shockpad to remain in a phase of low stiffness for longer periods.

Effect of Carpet Layer

The combination of the two carpet layers with shockpads of varying thickness provided measurements of whole pitch system behaviour. The introduction of a carpet layer above the 12 mm shockpad halved the peak impact forces measured on the shockpad alone. Both carpet systems were seen to exhibit similar force-deflection behaviour characteristics in terms of peak force and stiffness but did not show the same magnitude for both impactor types.

For the low energy ball impact, shockpad-carpet system behaviour was shown to be more affected by shockpad thickness in the water based system than the 3rd generation system. Both systems showed a peak impact force reduction of 100 N, however the water based system showed a greater increase in peak deflection over the range of shockpad thickness changes. The lack of change in the 3rd generation system due to shockpad thickness is attributed to the long carpet pile and 40 mm rubber and sand in-fill which are compacted and deformed before the load reaches the shockpad. The shockpad does not become as involved in the impact as only small loads are transferred though the carpet layer.

The Clegg Hammer impact is a higher energy impact and higher loads are transferred to the shockpad layer for both carpet types. Significant reductions in peak impact force and increases in peak deflections are produced by altering shockpad thickness. Stiffness in the final phase of behaviour is also reduced by using thicker shockpads for both carpet types. These results indicate that the shockpad thickness does not play such an important role in for the ball rebound behaviour of whole pitch systems, which is supported by the mechanical property results measured in Chapter 4, however, shockpad thickness is important for player interactions. The reductions in peak impact force and stiffness achievable through increasing shockpad thickness are important when considering reducing injuries.

Carpets used throughout this testing were new. In real synthetic pitch conditions the carpet pile wears down and rubber in-fill can become compacted. Over time, the behaviour of shockpad-carpet systems is expected to become more dominated by the behaviour of the shockpad as more force is transferred through the carpet layer. The associated increases in peak impact force, reduction in deformation and increasing final stiffness may therefore require an increase in the shockpad thickness required to produce the best compromise between player safety and performance for long term in-service conditions.

Stress-Strain Behaviour of Shockpads

Force-displacement data is most often used by researchers to model similar impacts (e.g. Carré et al, 2002). However, for shockpads of different thicknesses, force-deflection data has the same non-linear, hysteric curve but does not follow the same path that would produce model coefficients independent of thickness. Stress-strain behaviour of shockpads was calculated from the force-deflection behaviour to normalise for thickness variations and create a common behaviour for shockpads independent of thickness. Determining stress-strain behaviour removed much of the non-linearity during loading for ball impacts, resulting in a near constant elastic modulus of shockpads. However, the stress-strain graph for the Clegg Hammer impact displayed a similar non linearity to force-displacement behaviour.

At small strains (less than 10%), the stress-strain behaviour of shockpads and shockpad-carpet systems was seen to be independent of shockpad thickness. Some deviation occurred during the ball impacts on the thicker 15 and 20 mm shockpad which may be explained by the errors produced in approximating contact area between the ball and shockpad. At larger strains (greater than 10 %), the elastic modulus was high enough to transfer significant load to the foundation layer and form a composite shockpad-foundation system where the behaviour of the foundations also began to influence the measured behaviour. The resulting stress-strain behaviour shows promise for the development of a model to describe shockpad behaviour, particularly for shockpads greater than 12 mm in thickness.

Data Quality

Employing a method of measuring the behaviour of shockpads under dynamic impact conditions provided a more accurate representation of peak impact loads, peak deflection and stiffness than the quasi-static loading used by other researchers as the strain rate dependence of rubber properties has been well documented in literature. However, the characteristics of shockpad behaviour were common to both quasi-static and dynamic test methods; demonstrating a non-linear force-deflection relationship with hysteresis. The non-linear behaviour and energy losses are attributed to changes in the porous structure of the shockpad during compression, and to the dynamic properties of the constituent rubber and binder.

The force plate data collected for ball and Clegg Hammer impacts showed good correlation with the validation methods. Data for Clegg Hammer impacts showed a very strong correlation with peak deceleration output by the Clegg Hammer, and the small difference can be explained by different filters being used to smooth both sets of raw data. Peak deflections of the ball calculated from force plate data correlated well with peak deflections measured using high speed camera images. Although the force plate data showed a more rapid rate of loading, this was attributed to time lag for signal to reach the shockpad, filtering, possible distortion of the ball during impact and the resolution of the HSC sampling rate. Ball rebound height comparisons between force plate data and measured rebound heights were shown to be highly sensitive to the method used to filter the raw data and remove force plate resonance. The uncertainty in the value for rebound velocity imparted on the ball also has implications for energy return calculations.

The resonance produced by the force plate and the subsequent filtering required to smooth raw data was the source of most errors throughout shockpad behaviour measurement. The resonance produced uncertainty in locating the force-time coordinates where the impactor and shockpad decouple and this affected final deformation of the shockpad and energy returned to the ball. Filtering reduced the peak impact force, however, the contact time was able to remain unchanged. The force plate was also limiting as it gave a foundation layer more rigid than those used in actual pitch constructions. This affected the behaviour of thinner 8 and 12 mm shockpads more as higher forces were transmitted to the force plate, however a comparison of shockpad impact measurements recorded on concrete and tarmacadam by Young (2006) showed this to produce only small changes in shockpad mechanical properties.

While the force plate was limited by resonance and high rigidity, it provided an original method of determining the dynamic impact behaviour of shockpad over the traditional quasi-static hydraulic tensometer. The remote data collection by the force plate allowed the impact to occur as it would occur on an actual synthetic surface and actual rates of loading and peak forces to be measured rather than simulated by a tensometer. The high sampling rate achievable for data collection also minimised the amplification of errors that is produced by the numerous integrations of data required to determine velocity, deflection and energy return.

Assumptions were required to be made in the development of the experimental methodology for this testing programme as data could not be found in literature. As an example, the shockpad was assumed to deform to surround the ball as deformation increased while the ball remained rigid. In reality there may have been some gap between the ball and shockpad at the edge of contact and some deformation of the ball may have occurred. Equations do exist to determine the contact area, however the non linearity of shockpad stiffness could not be accounted for and therefore errors would have occurred. Such assumptions may be broad but necessary as the development and execution of testing was too in depth for the scope of this research project. These assumptions may have created small errors, but were considered adequately minimised for the purposes of an introductory examination of the impact behaviour of shockpads.

Summary

Factors identified by this testing programme that affect shockpad behaviour are summarised in Figure 5.36. The effect of shockpad design was demonstrated by reductions in peak impact force and final stiffness achieved though increasing shockpad thickness through a range of 8 to 20 mm. An additional effect of altering shockpad bulk density to delay the transition phase was also predicted. The effect of adjacent layers was also seen in the force-displacement behaviour of shockpads. The carpet layer reduced the force transmitted to the shockpad and the composite behaviour of the shockpad-foundation layer produced in thinner shockpads increased peak impact force and final stiffness. The impactor type, specifically mass, shape and drop height, were all shown to affect the shockpad behaviour though peak force, peak deflection and final stiffness. Although it was not investigated as part of this study, mechanical damage and ageing of the shockpad and carpet layers were hypothesised to also affect the behaviour demonstrated by shockpads.

5.4 Mechanical Modelling

5.4.1 Introduction

A review of literature did not find a model that adequately described shockpad behaviour. McCullough (1985) and Kim (1997) were the only researchers who had specifically attempted to model shockpad behaviour. Kim (1997) used a complex numerical model that provided only three data points during the loading phase. The non-linear and hysteretic behaviour exhibited by shockpads was not observed due to insufficient data points. McCullough (1985) used a non-linear damped model to describe foam shockpads constructed from distinctly different constituent materials to cast in-situ shockpads. Other researchers who have modelled similar impacts between rigid and compliant objects (Carre et al, 2002; Shorten and Himmelsbach,

2002) also either used complex numerical models, did not account for changes in behaviour due to thickness of the compliant layer or did not account for hysteresis.

The understanding of the physical impact behaviour of shockpads gained through this research project allows a mathematical model to be developed. Force-displacement models provide the most information in terms of shockpad behavioural characteristics as peak force, peak displacement, stiffness, energy returns and energy losses can be directly inferred. The stress-strain data analysed in Section 5.3.3 also showed promise for describing shockpad behaviour as it could normalise changes in shockpad thickness of 15 mm and above.

The aim for the development of a mathematical model was to provide a set of model coefficients that could be used in academia to assist in the development of composite synthetic surface models, for footwear-synthetic surface models and for biomechanics. The model would also assist the sports surfacing industry in engineering the shockpads to exhibit specific behaviours required for predictable ball behaviour and player interaction.

An ideal model would fulfil the following criteria:

- Accurately describe non-linear loading and unloading behaviour of shockpads
- Account for the hysteretic behaviour of shockpads
- Accurately predict peak impact forces
- Provide model coefficients to describe shockpad behaviour that account for shockpad mix design and impact method.

For the purposes of producing a mathematical model, a mechanical model was selected over a numerical model as it presented a first stage to the model development process. The more basic mechanical model allowed the sensitivity of coefficients to be assessed and it did not require as many assumptions as the more complex numerical model. The clearer understanding of the factors affecting the accuracy of the model, values for model coefficients and boundary conditions that result from the mechanical model could then be used as initial starting conditions for the development of a numerical model.

Mechanical models to describe rubber and other elastomeric materials detailed in literature range in complexity and accuracy. All mechanical models contain a combination of springs and dashpots in series or parallel configuration to represent the elastic and viscous components of elastomeric material behaviour. The most basic of models contains a linear spring to represent force-displacement behaviour, with more advanced models containing a parallel non-linear spring with a damper.

Five mechanical models of increasing complexity were used to describe the behaviour of shockpads and the shockpad-carpet systems. The models ranged from the basic linear model, the linear damped model evaluated by McCullough et al (1985), the non-linear model presented by Shorten and Himmelsbach (2002) and a combination of the models of McCullough et al (1985) and Shorten and Himmelsbach (2002) to describe non-linear damped model. A stress-strain model was also developed to describe the relationship between stress and strain of a shockpad during an impact. The equations for the five models are given by Equations 5.23 to 5.27.

Linear Model: $F = kx + F_0$ -------- Equation 5.23

Linear Damped Model: $F = kx + cv + F_o$ -------- Equation 5.24

Non-linear Model: $F = kx^n + F_o$ -------- Equation 5.25

Non-linear Damped Model: $F = kx^n + cv + F_o$ -------- Equation 5.26

Stress-Strain Model: $\sigma = E\varepsilon^a + d\dot{\varepsilon} + \sigma_o$ -------- Equation 5.27

Where:

F	=	Vertical Force	[N]
x	=	Displacement	[m]
v	=	Velocity	[m.sec^{-1}]
k	=	Stiffness Coefficient	[N.m^{-1}]
c	=	Damping Coefficient	[N.sec.m^{-1}]

n	=	Non Linearity Coefficient	-
F_o	=	Force offset	[N]
σ	=	Stress	[Pa]
ε	=	Strain	
E	=	Modulus	[Pa]
d	=	Damping Coefficient (strain)	[$N.sec.m^{-2}$]
$\dot{\varepsilon}$	=	Strain rate	[sec^{-1}]
α	=	Non Linearity Coefficient (strain)	
σ_0	=	Stress Offset	[Pa]

Each of the five models were compared to the force plate data for Clegg Hammer and hockey ball impacts for the range of shockpads 8 to 20 mm in thickness (12 to 20 mm for Clegg Hammer impacts) in the following section and their accuracy assessed. The coefficients for each model were optimised using a computer programme run through Matlab (Mathworks, Vers. 7.2) to provide the best correlation to force plate data and evaluated by a measurement of the percentage Root Mean Square Error (RMSE) compared to peak impact force (or stress). The most suitable model in describing shockpad behaviour was also compared to force plate data to determine the suitability of the model for describing the behaviour of shockpad-carpet systems.

5.4.2 Modelling Shockpad Behaviour

Five different mechanical models, increasing in order of complexity, were used to determine their suitability for accurately describing the behaviour of shockpads. All mechanical models used a force-displacement relationship to describe shockpad movement under Clegg Hammer and hockey ball impacts. Initially, each model was fitted to describe the behaviour of the benchmark shockpad. The non-linear damped model provided the best correlation to force plate data and was therefore used to describe the behaviour of shockpads of various thickness.

The linear, linear damped, non-linear and non-linear damped models are compared to force plate data for the benchmark shockpad in Figure 5.37 for Clegg Hammer impacts and Figure 5.38 for hockey ball impacts with model coefficients of k, n, c and F_o given in Table 5.3. The linear model represents a linear relationship between force and displacement, shown as a straight line. For the Clegg Hammer impact there are two points where the force plate data and model agree, resulting in a significant error of 20%. There is more agreement between the linear model and ball rebound force plate data with an RMS error of 20% and approximately seven common points during the loading phase. The model is not considered adequate in describing shockpad behaviour as it does not account for non linearity or energy losses, and underestimates peak force by 1000 N for both impact types.

An addition of a damper to the linear model improved the fit between model and force plate data. The model showed a linear relationship between force and displacement, however loading and unloading sections of the model did not overlap, showing energy was lost during the impact. RMS error for the two impacts showed the model had a better fit for both Clegg Hammer and hockey ball impacts with error values of 12% and 13% respectively. For both impacts, the linear damped model showed a better agreement with the unloading portion of the graph than the linear model, particularly for the ball impact. Its inability to describe non-linear behaviour resulted in a poor correlation with the loading section of the graph and also underestimated peak force by approximately 800N. The linear damped model displayed a better correlation to force plate data compared to the linear model, however it does not satisfy the criteria of an acceptable model.

The non-linear model used a stiffening non-linear spring to describe shockpad behaviour. Compared to the linear damped model, there is a reduction in correlation between the model and force plate data for both impact types. Error increases to 16% and 14% for hockey ball and Clegg Hammer impacts respectively, but the model still exhibits a better correlation than for the linear model. The non-linear spring gives a curve to the force-displacement behaviour, which lies between the loading and unloading curves of the force plate data with few common points, however peak force and the origin are much closer to being predicted than for the linear models. The introduction of the non-linear coefficient significantly raised the stiffness coefficient six orders of magnitude higher than the linear damped model for both types of impact. Although the non-linear model exhibits non-linear behaviour and there is improved prediction of the origin, there is no account for energy losses and there the model does not meet the criteria of an ideal model.

The addition of a damper to the non-linear model significantly improved the correlation between the model and force plate data. The relationship between the non-linear damped model and force plate data for the Clegg Hammer shows a good correlation for the loading behaviour, particularly in the transition and final stages of loading. However, the unloading behaviour is less well described resulting in an error of 5%. For the hockey ball impact, an excellent correlation exists between the model and force plate data giving an error of 2%. The non-linear damped mechanical model meets the criteria of accurately describing the non-linear and hysteretic behaviour of shockpads and accurately predicts peak force.

In order for the non-linear damped model to fulfil all criteria of a suitable model, it should also be able to describe shockpad behaviour independently of all shockpad mix design variables. Figure 5.39 and Figure 5.40 compare the non-linear damped model to force plate data for shockpads of thickness 8 to 20 mm for Clegg Hammer and hockey ball impacts respectively (12 to 20 mm for Clegg Hammer impacts). The non-linear damped model shows a good correlation with shockpads 12 to 20 mm in thickness for Clegg Hammer impacts. Model coefficients given in Table 5.4 vary with shockpad thickness but do not show any relationship. The error for the 15 mm shockpad is higher than the 12 and 20 mm shockpads, showing coefficients do not have such a strong fit compared to other shockpad thickness. A comparison of the model with force plate data in Figure 5.39 shows a good correlation during the loading phase only. It is unclear at this stage if the issue is a result of the shockpad, filtering of the force plate data or the model.

A comparison of the non-linear damped model to the force plate data for the hockey ball impact shows the same issues with increased error for the 15 mm shockpad. This suggests the issue may be a result of the shockpad itself. With the exception of the 15 mm shockpad model, the stiffness coefficient reduced from 5×10^9 to 3×10^6 N/m and the non linearity coefficient reduced from 2.7 to 1.7, displaying quantitatively the reduction in stiffness and increasing linearity observed in shockpad behaviour when shockpad thickness is increased. The model also predicts less deformation recovery of the shockpad compared to the force plate data for thicker shockpads, which relates to less energy returned to the ball and therefore lower ball rebound heights.

The non-linear damped model shows a good correlation to the force-displacement behaviour of shockpads varying in thickness. However, model coefficients vary with shockpad thickness and therefore do not satisfy the criteria of being independent of design. The stress-strain model was used to normalise shockpad thickness and determine an equation to describe shockpad behaviour independent of shockpad thickness.

The stress-strain model is compared to force plate data for a hockey ball impact on shockpads of varying thickness in Figure 5.41. The correlation between the model and force plate data improves as shockpad thickness increases, with the error (given in Table 5.5) reducing from 12 to 7% of the peak stress. The model shows a better correlation for the hockey ball impact than the Clegg Hammer impact shown in Figure 5.42. Errors (Table 5.6) reduce from 15 to 6%, indicating the model is better at describing the lower energy impacts and thicker shockpads. A lower correlation occurs between the model and force plate data during the unloading section of the graph particularly for thicker shockpads where greater energy return is shown for the force plate data than the stress-strain model. As identified for the non-linear damped model, issues with removing the resonance from force plate data using a filter have produced small errors within the force plate data, indicating the model might describe shockpad behaviour upon unloading more accurately than it would seem from the error calculations. This difference is described in further detail in Section 5.3.5.2.

Model coefficients show a relationship of decreasing elastic modulus and non-linearity coefficient with increasing shockpad thickness. The relationship is less clear for damping coefficient and stress offset. The optimised non-linearity coefficient for the ball impact was less than one for the 15 and 20 mm shockpads, indicating a strain softening rather than stiffening observed for thinner shockpads and for the Clegg Hammer impacts. This may have been more a result of the contact area between the ball and shockpad and the complex strain dynamics that occur at this interface.

The aim of producing a stress-strain model was to normalise shockpad thickness and determine a set of model coefficients to describe shockpad behaviour independently of design. For both Clegg Hammer and hockey ball impacts, variation between model coefficients did not fall within acceptable limits. Model data for shockpads 15 and 20 mm in thickness showed coefficients were beginning to plateau, however it appeared the foundation layer affected shockpads of all thicknesses over the range tested. The stress-strain model was therefore not capable of describing shockpad behaviour independently of shockpad design.

5.4.3 Modelling Shockpad-Carpet System Behaviour

The non-linear damped model was compared to the force plate behaviour of shockpad-carpet systems to determine if was also suitable for describing composite systems. Comparisons of the force plate data for two benchmark shockpad-generic carpet systems and optimised non-linear damped model are made in Figure 5.43 and Figure 5.44 for Clegg Hammer and hockey ball impacts respectively.

The similarity between the force plate data for water based and 3rd generation carpet systems is also displayed in the similarity of model coefficients shown in Table 5.7. Model coefficients for hockey ball impacts on the two carpet systems show less similarity (Table 5.8), with stiffness increasing by the power of 3 and a 1.5 increase in non linearity coefficient between water based and 3rd generation systems. Damping and force offset were similar for the ball impact of the two systems.

Visually, a good correlation was seen between the non-linear damped model and force plate data for both impact types on the water based and 3rd generation systems. As observed in modelling shockpads alone, the recovery of the shockpad during unloading is not described by the model, producing significant errors. The recovery, a result of the filtering procedure, is extended by resonance of the force plate and was not observed in shorter impacts. This suggests the force plate data recovery may be over exaggerated and the model is more accurate in describing shockpad behaviour that it would appear from the errors.

5.4.4 Discussion of Mechanical Modelling

The mechanical model which best described shockpad behaviour was the non-linear damped model. This result was expected as it combined both the variable non-linear coefficient used by Shorten and Himmelsbach (2002) with the damping term used by McCullough et al (1985). The model constituted a parallel non-linear spring and damper to accurately describe shockpad behaviour and satisfied more criteria than the other mechanical models examined. Non-linear loading and unloading behaviour are well described and peak loads are also predicted with good accuracy. However, stiffness, non linearity and damping coefficients were dependent on shockpad thickness and therefore no set of model coefficients could be used to describe shockpad behaviour independently of design. Model coefficients were also shown to vary with impactor energy, also hindering the development of a 'global' model to describe shockpad behaviour.

A comparison of the non-linear damped model with force plate data shows a good fit with low errors. The main source of error, particularly for thicker shockpads, is the 'measured' long recovery of shockpads during unloading compared to the model which predicts the ball and shockpad decouple while significant deformation of the shockpad remains. Issues identified in the examination of shockpad behaviour showed the force plate data to overestimate the residual deformation of the shockpad, most likely due to resonance of the force plate, and therefore the model is most likely predicting better actual shockpad behaviour than occur in reality.

A mechanical model describing force-deflection is useful as it directly provides important characteristics to predict and describe shockpad behaviour such as peak force, stiffness and energy return. However, the coefficients determined are dependent on shockpad thickness and impactor type, and thus in its present form the model is not ideal for modelling shockpads. The stress-strain model allowed deflections to be normalised against shockpad thickness and it was anticipated that it would produce a mathematical relationship independent of shockpad design.

The rigid force plate below the shockpad influenced stress-strain behaviour of the shockpads 8 to 20 mm in thickness preventing an equation describing generic shockpad behaviour from being accurately determined. Overall, stress-strain model coefficients lie within a smaller range than the non-linear damped model, particularly the stiffness/elastic modulus. However, the stress-strain model displayed too much variability, particularly for the thinner 8 and 12 mm shockpads to accurately determine a set of coefficients to describe generic shockpad behaviour. The effect of impactors of different mass was also not normalised by the stress-strain graph, however impactor shape could be accounted for in the calculation of stress.

Non-linear damped models were unable to describe shockpad behaviour independently of shockpad thickness and impactor type, however in its current form showed a good correlation with force plate data. The need for the offset force coefficient to translate the model data to the origin to coincide with force plate data was a result of using a constant damping coefficient to describe all stages of shockpad behaviour. In the initial stages of behaviour, the elastic component of the model was small due to low deflection, however, the viscous component was comparatively large due to the large damping coefficient to describe later viscous behaviour and therefore there was a need for an offset force to cancel the large viscous term. Further development of the model to incorporate a non-linear damping coefficient that is displacement (or strain) dependent may negate the need for an offset force. A further drawback of using a non-linear model was the non-linear coefficient used to describe stiffening behaviour. The term to describe the non-linear elastic behaviour required significantly larger stiffness coefficients, k, to be used than linear models to achieve the required peak force. This presents a problem when comparing the stiffness of shockpads to more linear materials such as metals and concrete.

Further use of the non-linear damped model to describe shockpad behaviour as part of a composite shockpad-carpet pitch structure would require the thickness to be included in the model. Model coefficients were relatively independent of shockpad thickness for the Clegg Hammer impact but vastly different in terms of the elastic component (k and n) for the ball impact. Therefore, when modelling the shockpad and carpet as a single element each shockpad-carpet combination would require individual testing to determine combined behaviour. Conversely, developing a model that employs the carpet, shockpad and foundation layers as single elements would allow the substitution of different layers to determine behaviour, rather than testing each carpet with a multitude of different carpets. Therefore, models of shockpad and carpet systems are recommended to represent the shockpad and carpet layers as two separate layers due to inaccuracy involved in representing the behaviour of two distinctly different materials as one element.

The development of a basic mechanical model to describe shockpad behaviour was satisfied by the non-linear damped model which was capable of describing the three phases of behaviour. However, the use of a mechanical model is limited as it assumes the layer to be homogeneous, for deformation to occur throughout the thickness of the layer simultaneously and only describes two dimensional behaviour. Development of a numerical model which is able to accurately describe non-linearity and hysteresis would address these issues and provide a more detailed description of the strain gradients across the thickness and surrounding area.

5.5 Summary of Shockpad Behaviour and Modelling

A study of the impact behaviour of shockpads, the effect of mix design on this impact behaviour and the development of a suitable model to describe impact behaviour was prompted by the lack of knowledge within the sports surface industry and academia. In addition, data to describe shockpad and composite shockpad-carpet system behaviour was required to assist in the development of a model for synthetic pitch development and biomechanics research.

Three distinct phases of behaviour were observed for the Clegg Hammer and hockey ball impacts on shockpads; air void compression, transition and rubber compression. The first phase of behaviour involved compression of the larger air voids within the shockpad and was characterised by low stiffness. Upon compression of the larger air voids, the shockpad reached a transition point where the air void compression became increasingly difficult and rubber contact points increased. The third phase of behaviour involved compression of the rubber particles themselves and therefore a comparatively higher stiffness.

Clegg Hammer and Hockey ball impacts were shown to produce the same characteristic behaviour; non-linear stiffness and hysteresis. However, the different mass, shape and drop heights of the two impactors produced force-deflection behaviour that varied in terms of peak impact force and deflection and also the final stiffness of shockpads. Shockpad thickness was also shown to affect peak impact force and deflection and final stiffness. This effect of increasing shockpad thickness on reducing peak impact force and final stiffness for Clegg Hammer impacts highlighted how shockpad design could play an important role in injury prevention. The energy return of shockpads, which influence player performance and ball rebound characteristics, was shown to increase with shockpad thickness for both impact types. However, the effect of force plate resonance and the subsequent filtering increased the energy return of thicker shockpads, making it unclear of the actual energy returned to the ball and players. Force-deflection behaviour was also converted to stress-strain to normalise the effect of thickness. Thin shockpads achieved sufficient stiffness during impacts to cause significant stress transference to the foundation layer below. This stress transference produced a shockpad-foundation composite system, whereby the properties of the rigid foundation layer had some influence on the measured behaviour.

The addition of the carpet layer was shown to reduce the force transmitted to the shockpad. Increasing shockpad thickness below the carpet layers was not shown to have a significant effect on peak impact force reduction for lower energy ball impact. However, a significant reduction in peak impact force and final shockpad stiffness (Phase 3) was measured for increases in shockpad thickness for both carpet types using the Clegg Hammer. Shockpad thickness in whole pitch systems therefore has a role to play in reducing player injuries.

Validation of the force plate data was performed using three methods; peak deceleration comparison, high speed camera deflection measurements and ball rebound height measurements. Peak deceleration and peak deflection measurements from force plate data agreed well with validation measurements. Measured ball rebound heights were lower than those predicted by the force plate data. This error was attributed to the sensitivity of the point of decoupling between shockpad and ball on the ball rebound height which was affected by the filtering procedure.

The non-linear damped model, represented by a parallel non-linear spring and damper, was shown to be the most accurate mechanical model to represent shockpad behaviour; however, it was unable to describe shockpad behaviour independently of thickness or impactor energy. A stress-strain model, based on the non-linear damped force-displacement model, was developed to normalise shockpad thickness and account for impactor area, however the behaviour of thinner 8 and 12 mm shockpads was too influenced by the foundation layer to describe a 'generic' set of coefficient to describe shockpad behaviour. Attempts to employ the same non-linear damped model to shockpad-carpet systems, showed a correlation between model and force plate data. However, the effect of shockpad thickness would require each carpet to be tested with each shockpad thickness for each new product developed. Carpet, shockpad and foundation were recommended to be represented by single elements when modelling whole pitch systems. The findings of this model provide a good basis to the development of numerical model which is capable of describing the strain gradients that exist across the thickness of the shockpad.

Characteristic	Hockey Ball	Clegg Hammer
Mass	0.16 kg	2.25 kg
Shape	Spherical	Cylindrical
Diameter	70.8 mm	50 mm
Drop Height	1.5 m	0.45 m

Table 5.1: Characteristics of mass types used to impact shockpads and shockpad-carpet systems

Shockpad Thickness & Carpet Type	Impactor Type	Energy Input [J]	Energy Return [%]	Energy Loss [%]
8 mm SP	Hockey Ball	2.35 (0.00)	51.1 (0.06)	48.9 (0.60)
	Clegg Hammer	-	-	-
12 mm SP	Hockey Ball	2.33 (0.03)	47.9 (0.04)	52.1 (0.03)
	Clegg Hammer	9.93 (0.00)	46.3 (0.26)	53.7 (0.26)
15 mm SP	Hockey Ball	2.35 (0.00)	49.4 (0.05)	50.6 (0.05)
	Clegg Hammer	9.93 (0.00)	47.6 (0.24)	52.4 (0.24)
20 mm SP	Hockey Ball	2.35 (0.00)	51.1 (0.11)	48.9 (0.11)
	Clegg Hammer	9.93 (0.00)	50.9 (0.12)	49.1 (0.12)
WBC	Hockey Ball	2.35 (0.00)	30.2 (0.12)	69.8 (0.21)
	Clegg Hammer	9.93 (0.00)	18.9 (0.20)	81.1 (0.12)
3GC	Hockey Ball	2.35 (0.00)	21.3 (0.21)	78.7 (0.24)
	Clegg Hammer	9.93 (0.00)	28.0 (0.12)	72.0 (0.06)
8 mm SP + WBC	Hockey Ball	2.35 (0.00)	34.0 (0.01)	65.9 (0.01)
8 mm SP + 3GC	Hockey Ball	2.35 (0.00)	32.3 (0.09)	67.7 (0.03)
8 mm SP + WBC	Clegg Hammer	9.93 (0.00)	32.3 (0.11)	67.7 (0.11)
8 mm SP+ 3GC	Clegg Hammer	9.93 (0.00)	38.5 (0.09)	61.5 (0.09)
12 mm SP + WBC	Hockey Ball	2.35 (0.00)	35.7 (0.01)	64.3 (0.01)
12 mm SP + 3GC	Hockey Ball	2.35 (0.00)	34.5 (0.12)	65.5 (0.05)
12 mm SP + WBC	Clegg Hammer	9.93 (0.00)	35.7 (0.09)	64.3 (0.09)
12 mm SP + 3GC	Clegg Hammer	9.93 (0.00)	41.8 (0.31)	58.2 (0.31)
15 mm SP + WBC	Hockey Ball	2.35 (0.00)	39.6 (0.20)	60.4 (0.14)
15 mm SP + 3GC	Hockey Ball	2.35 (0.00)	40.4 (0.12)	59.6 (0.21)
15 mm SP + WBC	Clegg Hammer	9.93 (0.00)	39.2 (0.10)	60.8 (0.10)
15 mm SP + 3GC	Clegg Hammer	9.93 (0.00)	43.4 (0.13)	56.6 (0.13)
20 mm SP + WBC	Hockey Ball	2.35 (0.00)	43.0 (0.07)	57.0 (0.02)
20 mm SP + 3GC	Hockey Ball	2.35 (0.00)	46.0 (0.10)	54.0 (0.05)
20 mm SP + WBC	Clegg Hammer	9.93 (0.00)	43.4 (0.12)	56.6 (0.12)
20 mm SP + 3GC	Clegg Hammer	9.93 (0.00)	44.6 (0.09)	53.4 (0.09)

Table 5.2: Energy input, return and loss for shockpads and shockpad-carpet systems with shockpads of various thickness. WBC= Water based carpet. 3GC=3rd generation carpet. Standard deviations denoted in brackets

Model	Shockpad Thickness [mm]	Coefficients				RMSE [N]	Error [%]
		k [N.m^{-1}]	n	c [N.sec/m]	F_o [N]		
Linear	12	0.215 x 10^6	-	-	-238	234	20
Linear Damped	12	3.08 x 10^5	-	70	-718	147	13
Non-linear	12	4.74 x 10^{11}	3.8	-	119	187	16
Non-linear Damped	8	5.65 x 10^9	2.7	65	-396	93	5
	12	1.06 x 10^8	2.1	75	-42	24	2
	15	2.94 x 10^6	1.6	27	-41	50	6
	20	3.02 x 10^6	1.7	15	-42	30	5

Table 5.3: Coefficients and RMS error values for various models to describe shockpad behaviour for hockey ball impacts

Model	Thickness [mm]	Coefficients				RMSE [N]	Error [%]
		k [N.m^{-1}]	n	c [N.sec/m]	F_o [N]		
Linear	12	0.85 x 10^6	-	-	1074	968	20
Linear Damped	12	1.13 x 10^6	-	504	2794	589	12
Non-linear	12	8.83 x 10^{13}	4.6	-	556	686	14
Non-linear Damped	12	1.28 x 10^9	2.4	449	1080	239	5
	15	2.45 x 10^9	2.7	164	109	282	8
	20	2.92 x 10^8	2.5	131	111	196	7

Table 5.4: Coefficients and RMS error values for various models to describe shockpad behaviour for Clegg Hammer impacts

Shockpad Thickness [mm]	Coefficients				RMSE [Pa]	Error [%]
	E [Pa]	α	d [N.sec/m^2]	σ_o [Pa]		
8	0.5 x 10^7	2.3	200	-100 000	198 619	12
12	0.27 x 10^7	1	770	-400 000	76 920	8
15	0.13 x 10^7	0.5	300	-300 000	42 137	8
20	0.11 x 10^7	0.4	240	-260 000	29 395	7

Table 5.5: Coefficients and RMS error values for stress-strain model to describe hockey ball impact on shockpads 8 to 20 mm in thickness

Shockpad Thickness [mm]	Coefficients				RMSE [Pa]	Error [%]
	E [Pa]	α	d [N.sec/m^2]	σ_0 [Pa]		
12	1.6 x 10^7	2.3	30	-700 000	144 571	15
15	0. 9 x 10^7	2.1	1 800	-300 000	250 178	14
20	0.59 x10^7	1.6	2 000	-300 000	200 565	6

Table 5.6: Coefficients and RMS error values for stress-strain model to describe Clegg Hammer impact on shockpads 12 to 20 mm in thickness

System Type	Coefficients				RMSE [N]	Error [%]
	k [N.m^{-1}]	n	c [N.sec/m]	F_o [N]		
Water based	5.85 x 10^7	2.2	300	-890	437	18
3rd Generation	3.31 x 10^7	2.1	250	-750	344	14

Table 5.7: Coefficients and RMS error values for non-linear damped model to describe Clegg Hammer impact on standard shockpad-carpet systems

System Type	Coefficients				RMSE [N]	Error [%]
	k [N.m^{-1}]	n	c [N.sec/m]	F_o [N]		
Water based	0.26 x 10^7	1.8	40	-210	70	12
3rd Generation	110 x 10^7	3.3	30	-160	62	9

Table 5.8: Coefficients and RMS error values for non-linear damped model to describe hockey ball impact on standard shockpad-carpet systems

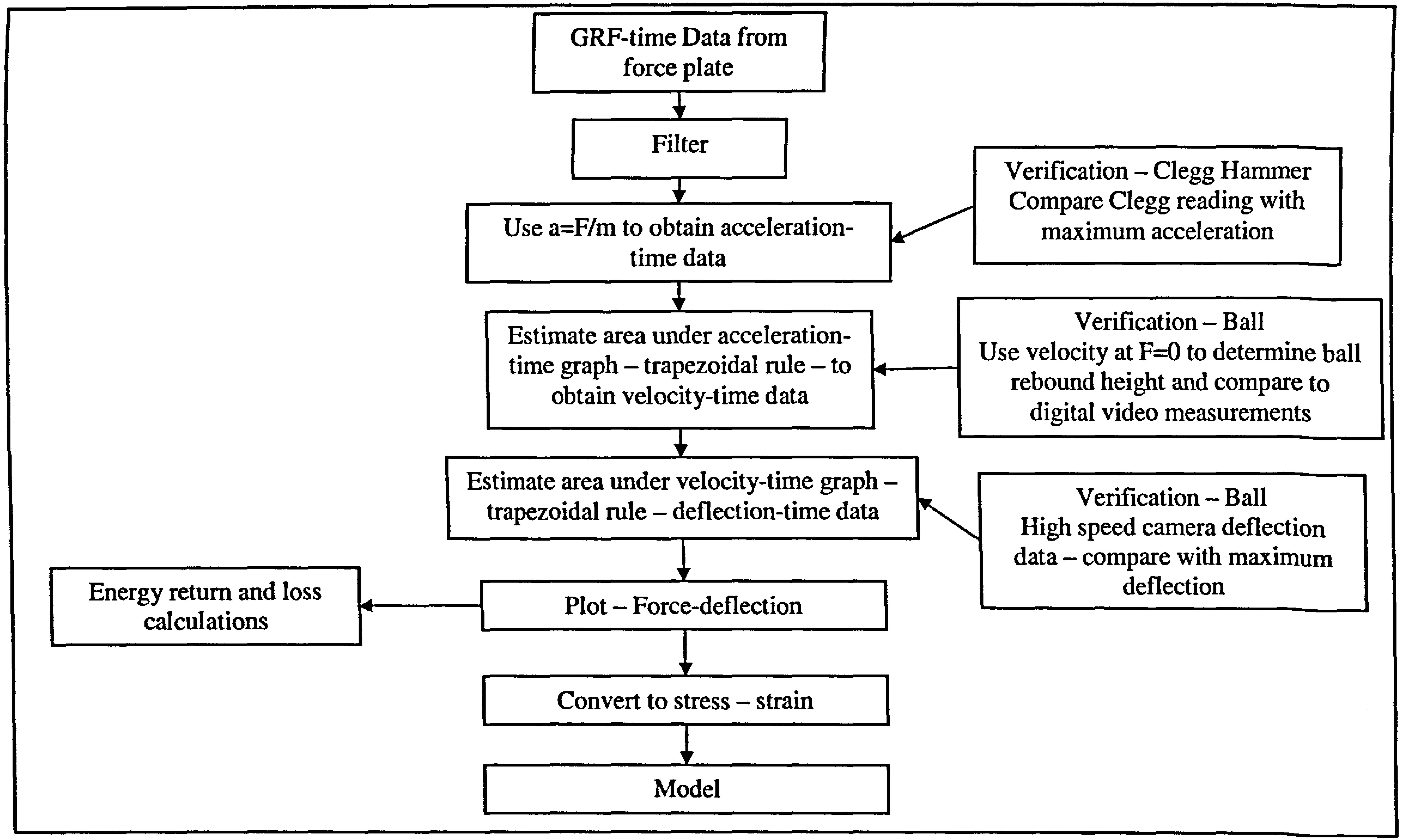


Figure 5.1: Flowchart demonstrating how data collected from the force plate was used to demonstrate shockpad behaviour and methods of verification

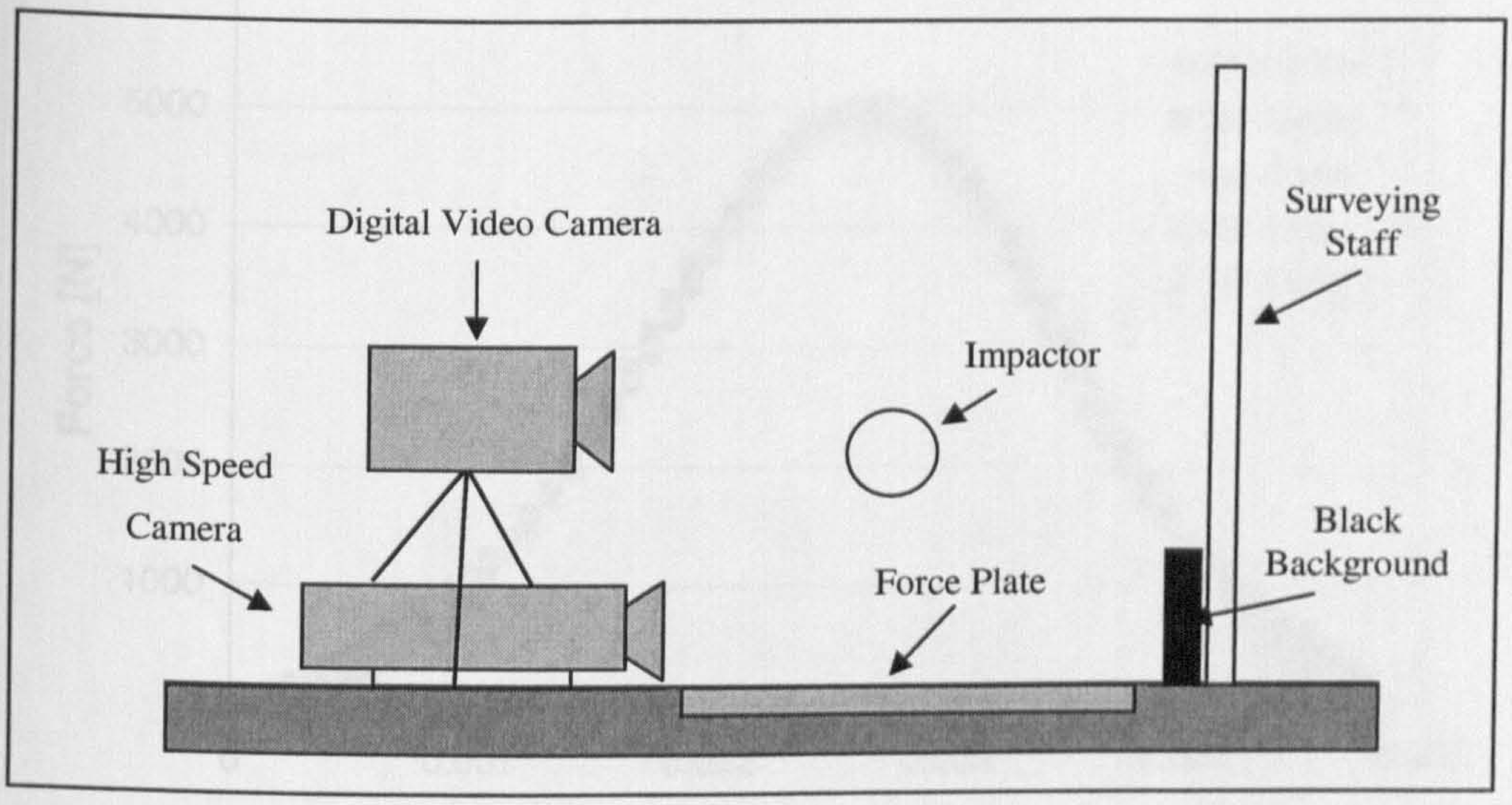


Figure 5.2: Force Plate Set-up

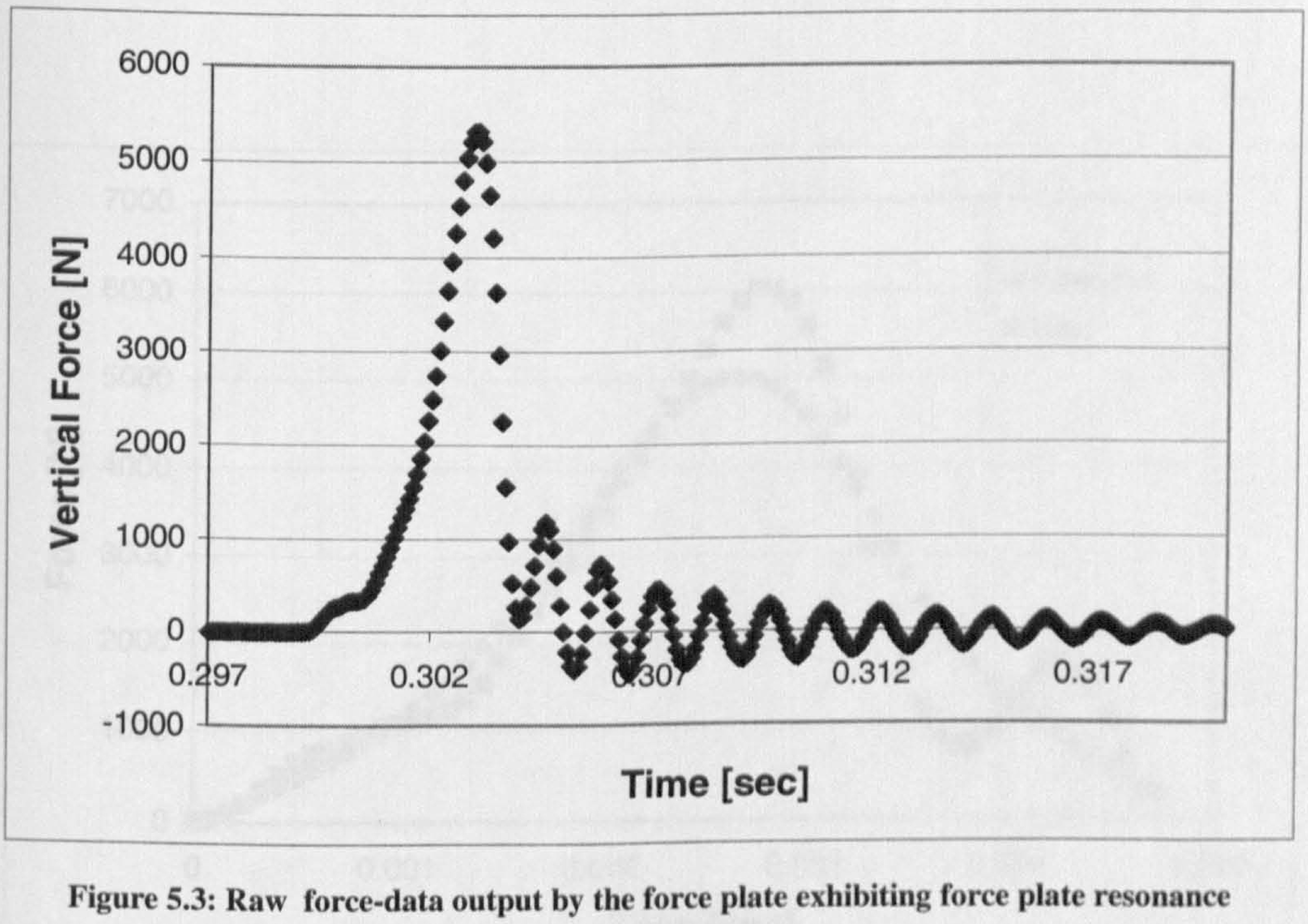


Figure 5.3: Raw force-data output by the force plate exhibiting force plate resonance

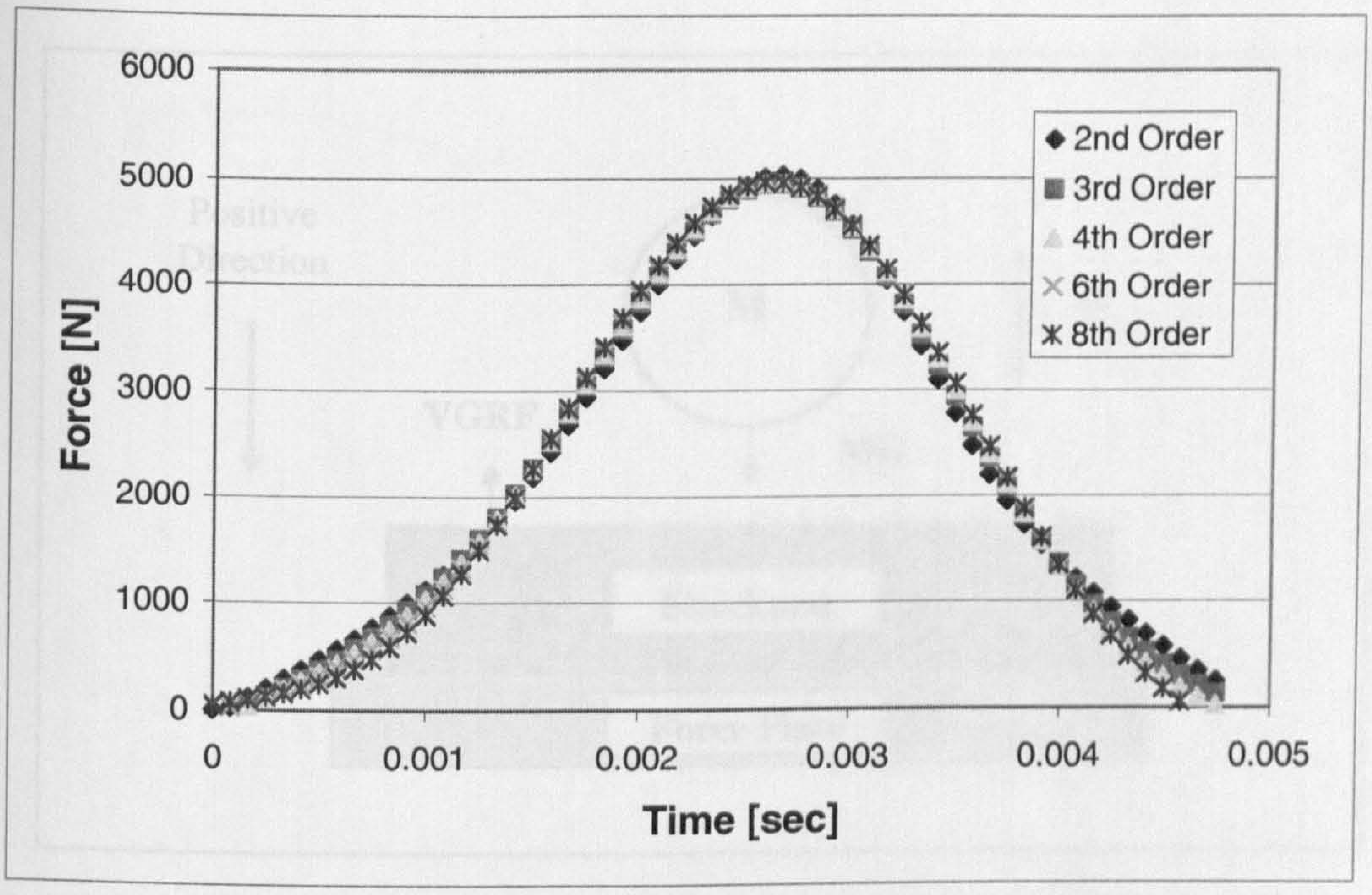


Figure 5.4: Range of orders for a Butterworth filter (0.065 cut off)

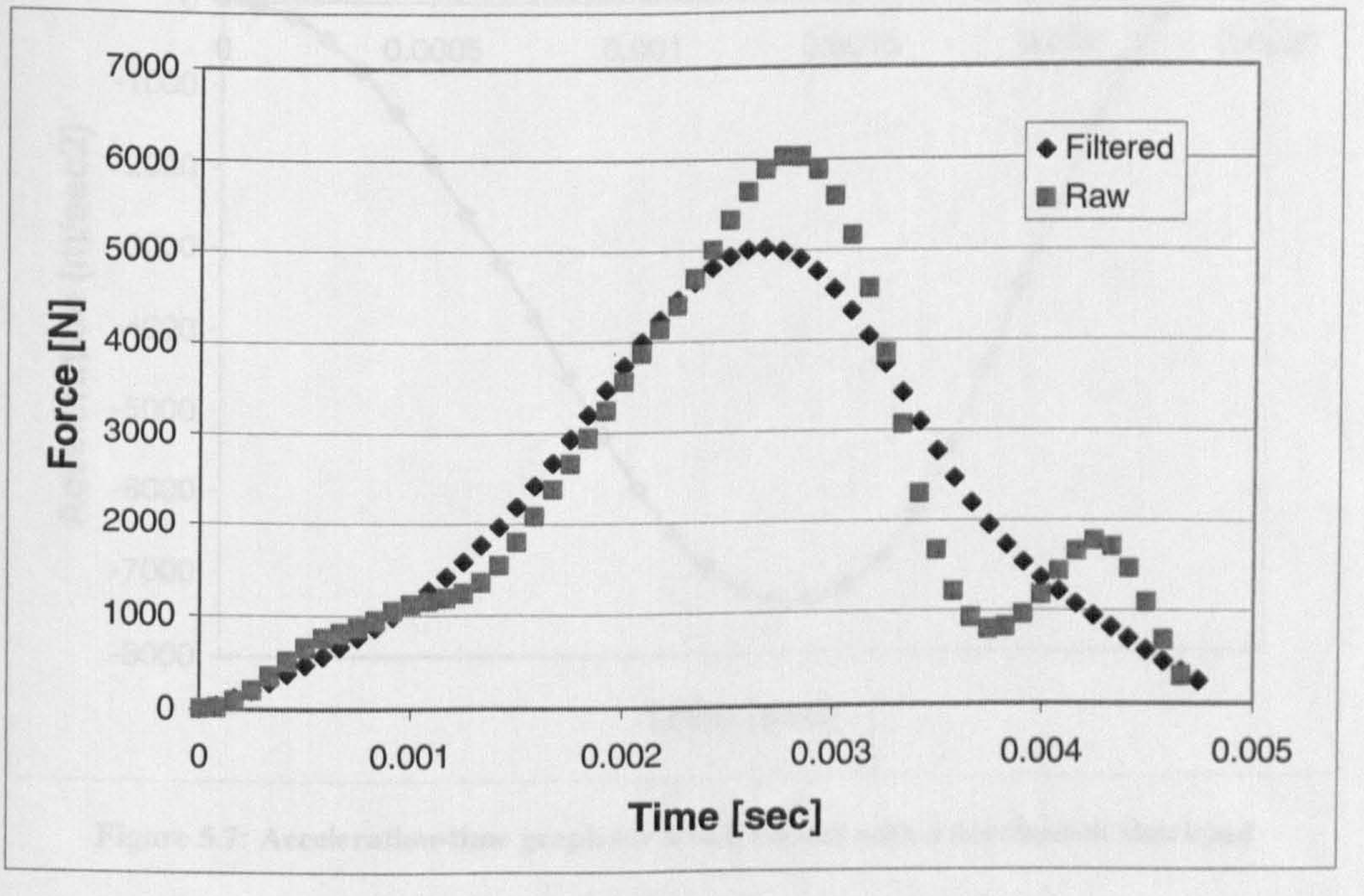


Figure 5.5: Unfiltered and filtered force-time data

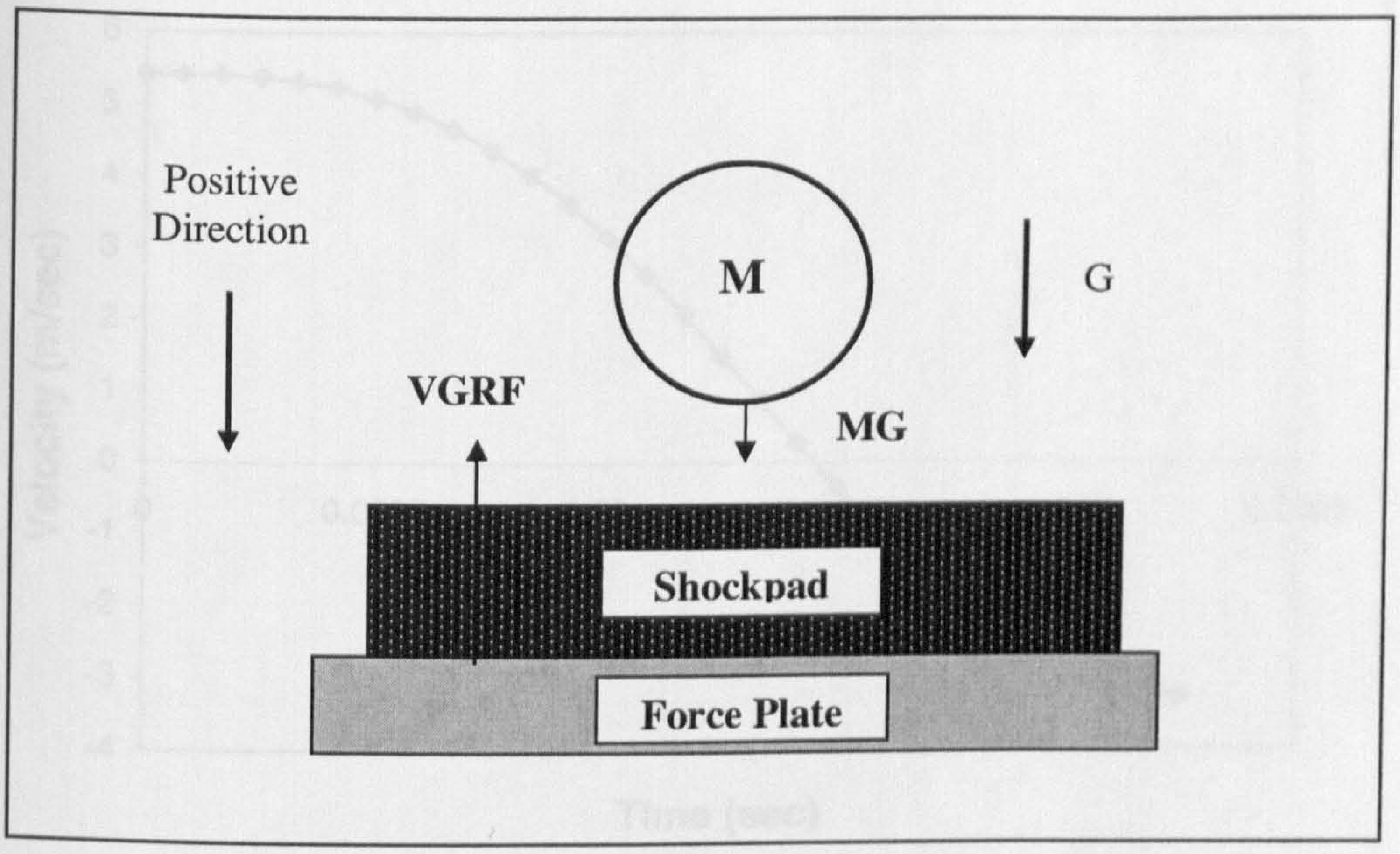


Figure 5.6: Free body diagram of mass impacting a shockpad

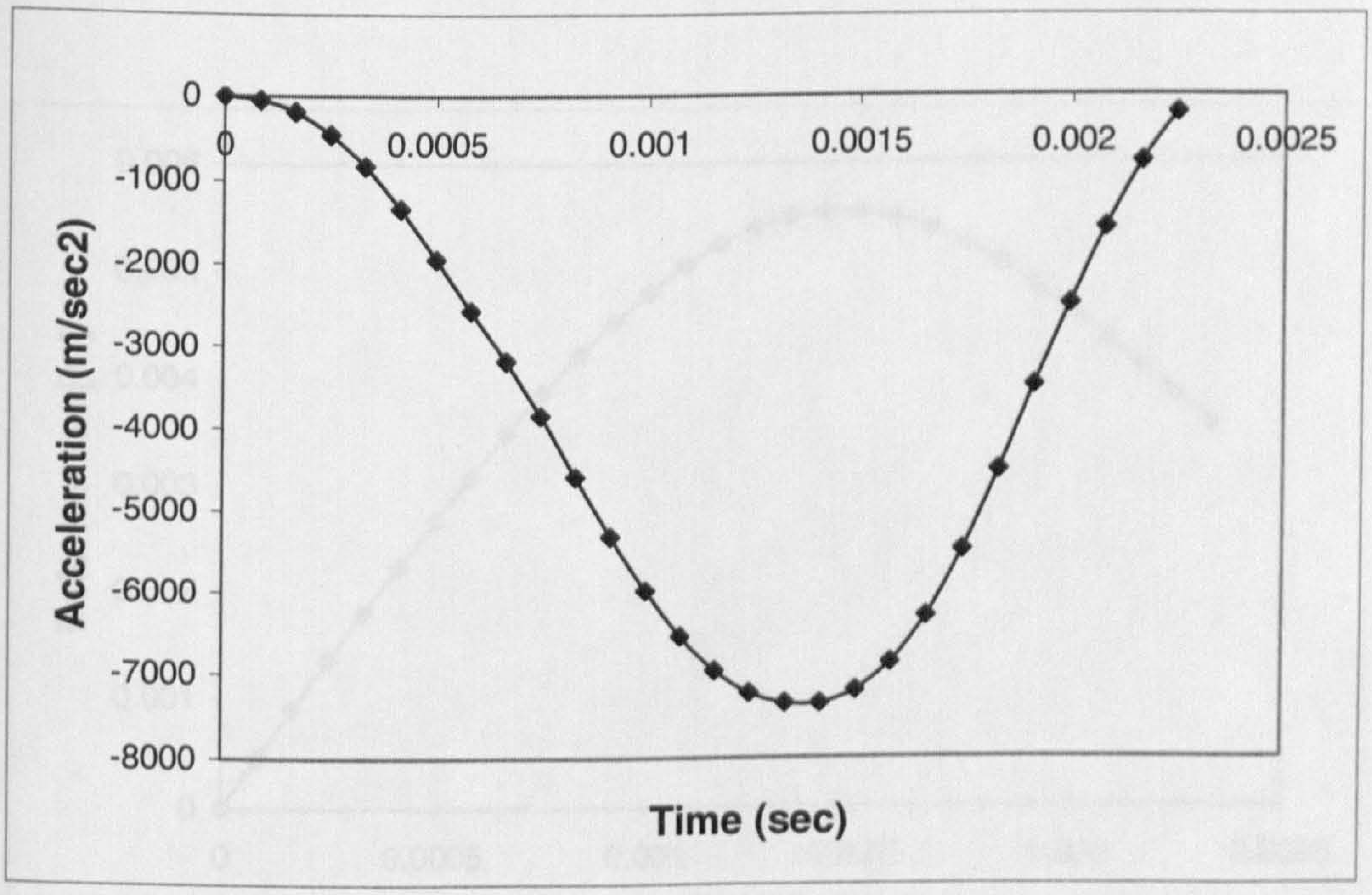


Figure 5.7: Acceleration-time graph for a ball impact with a benchmark shockpad

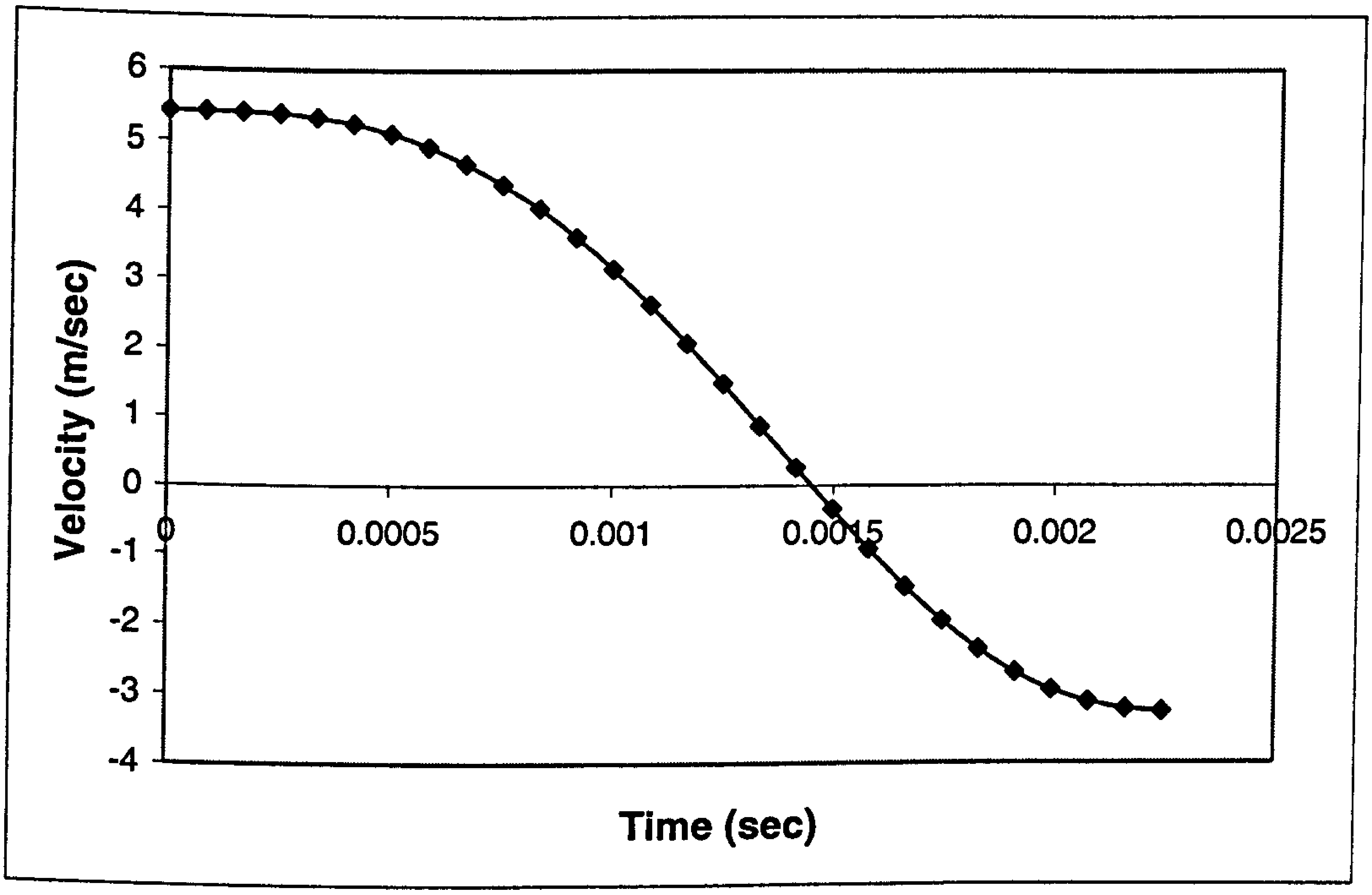


Figure 5.8: Velocity-time graph for a ball impact with a benchmark shockpad

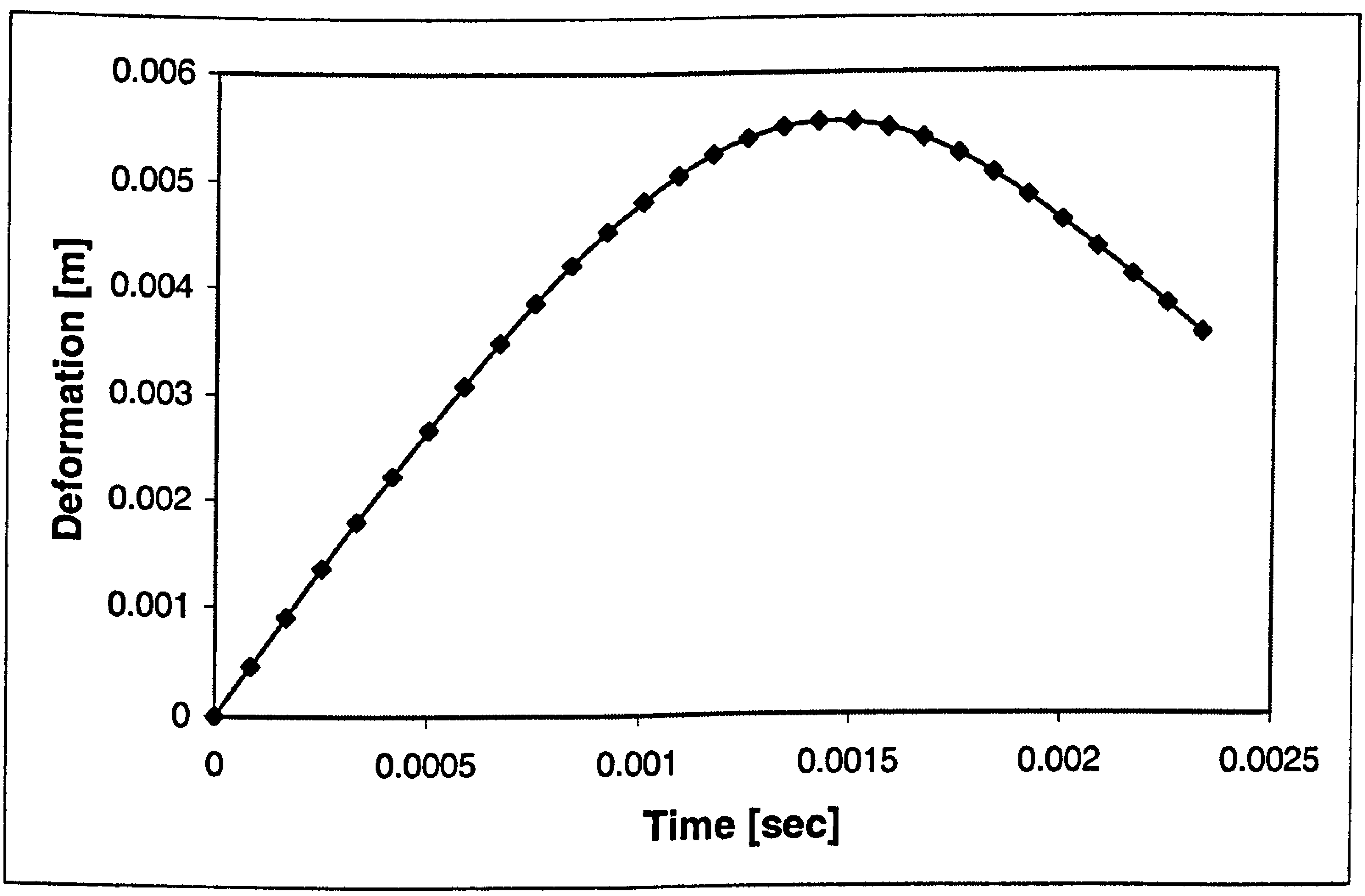


Figure 5.9: Deflection-time graph for a ball impact with a benchmark shockpad

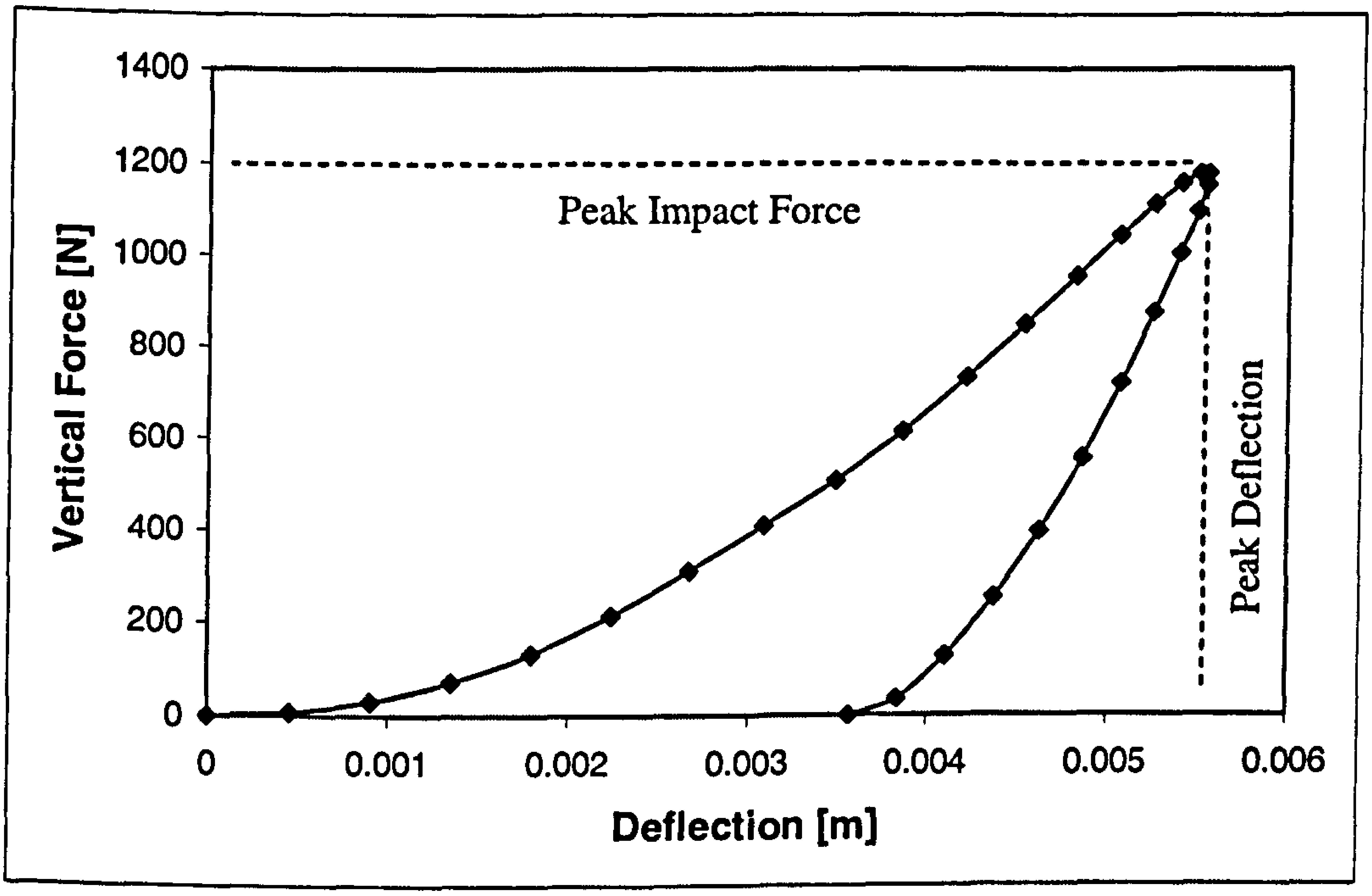


Figure 5.10: VGRF-deflection graph for a ball impact with a benchmark shockpad

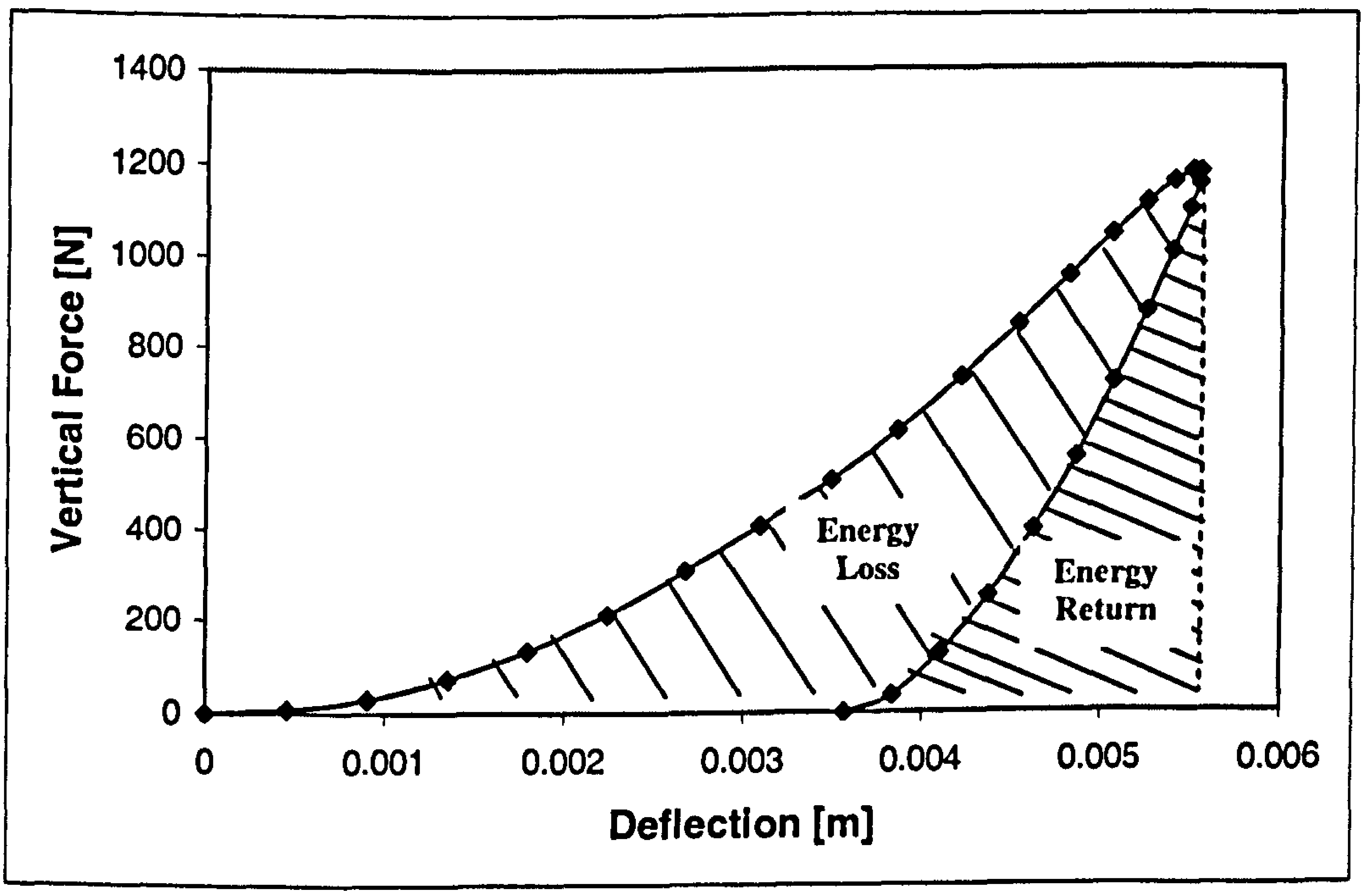


Figure 5.11: Force-deflection graph for a typical ball impact with a shockpad showing areas of energy return and loss

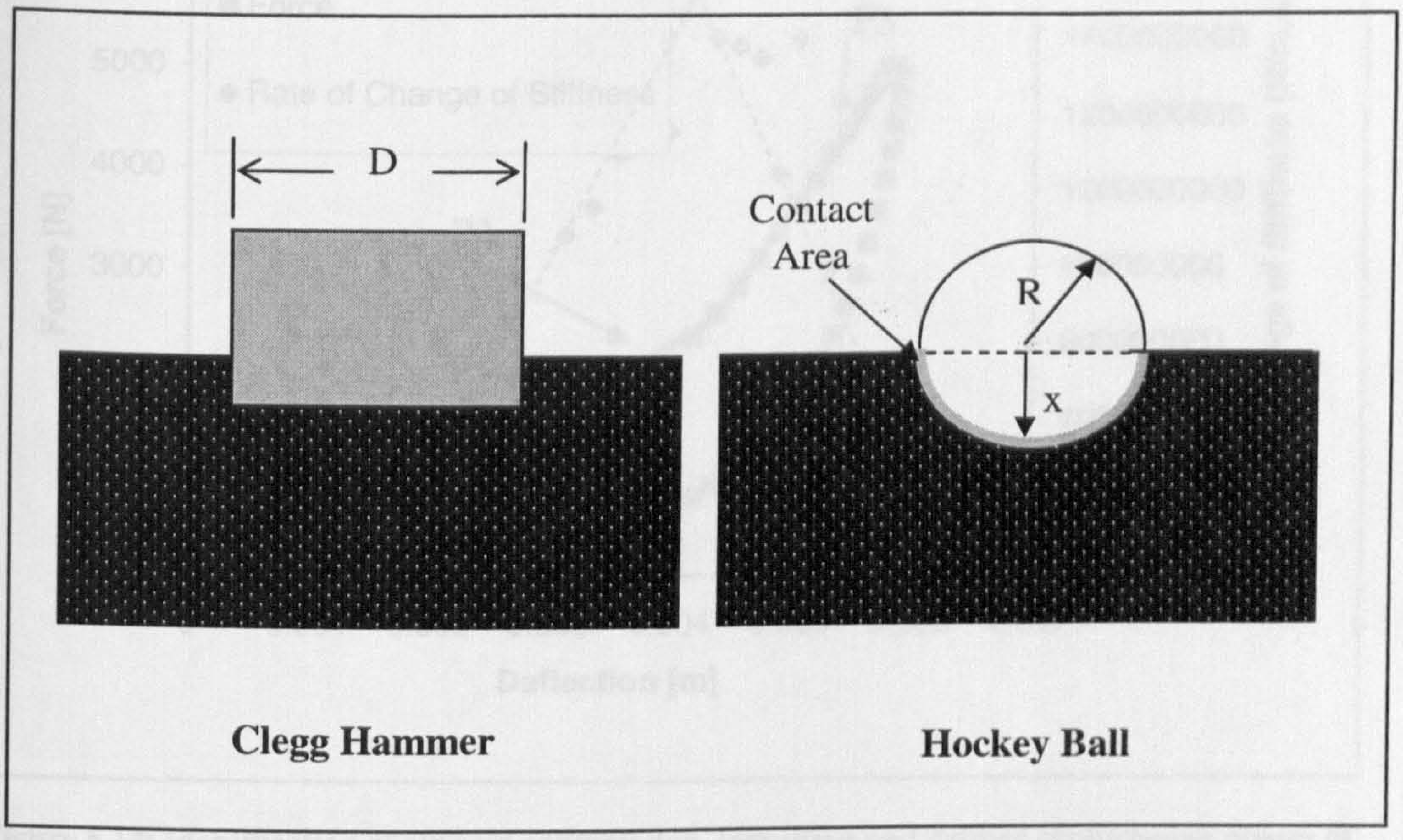


Figure 5.12: Shockpad and shockpad-carpet system dimensions for stress calculations

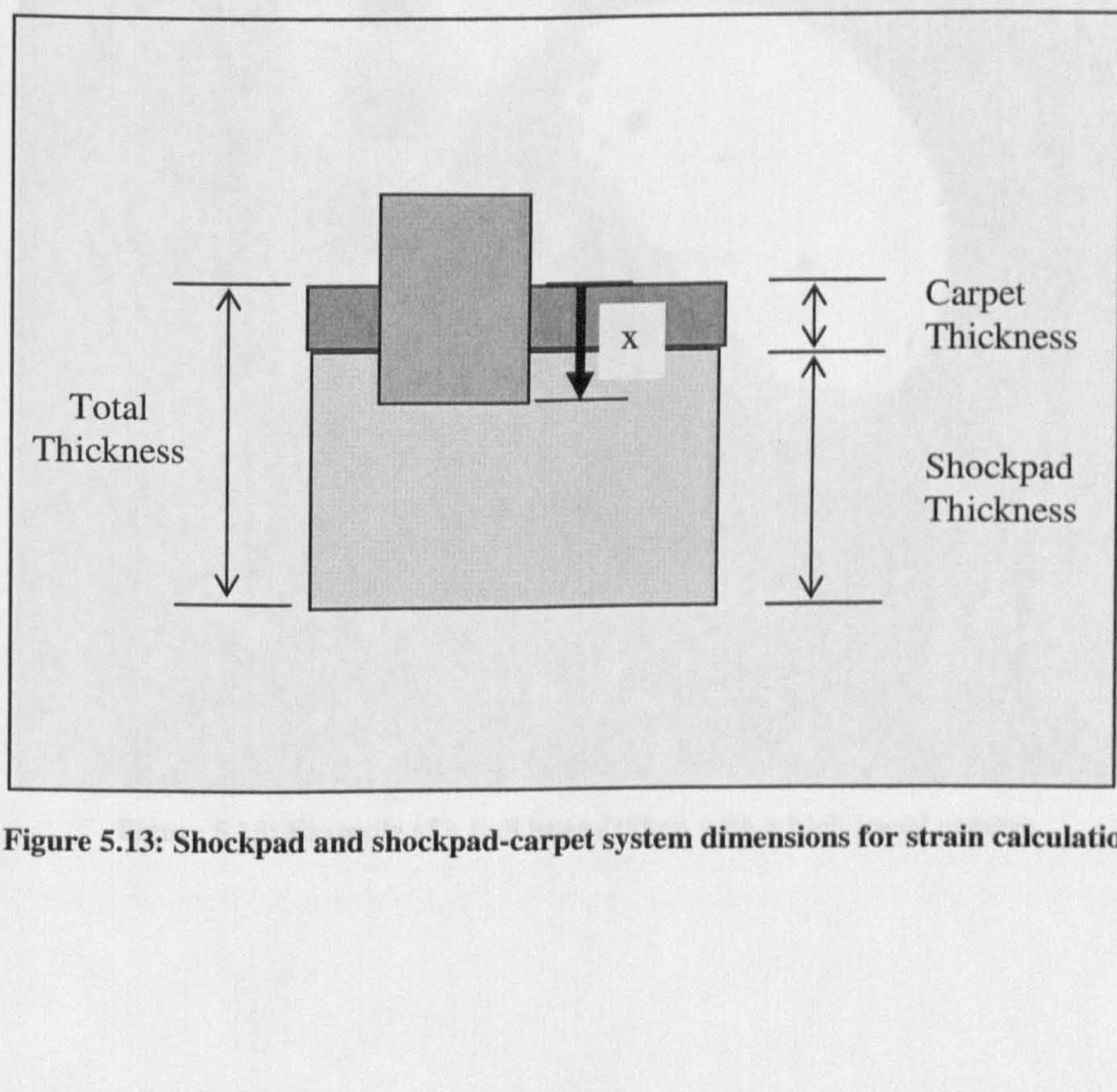


Figure 5.13: Shockpad and shockpad-carpet system dimensions for strain calculations

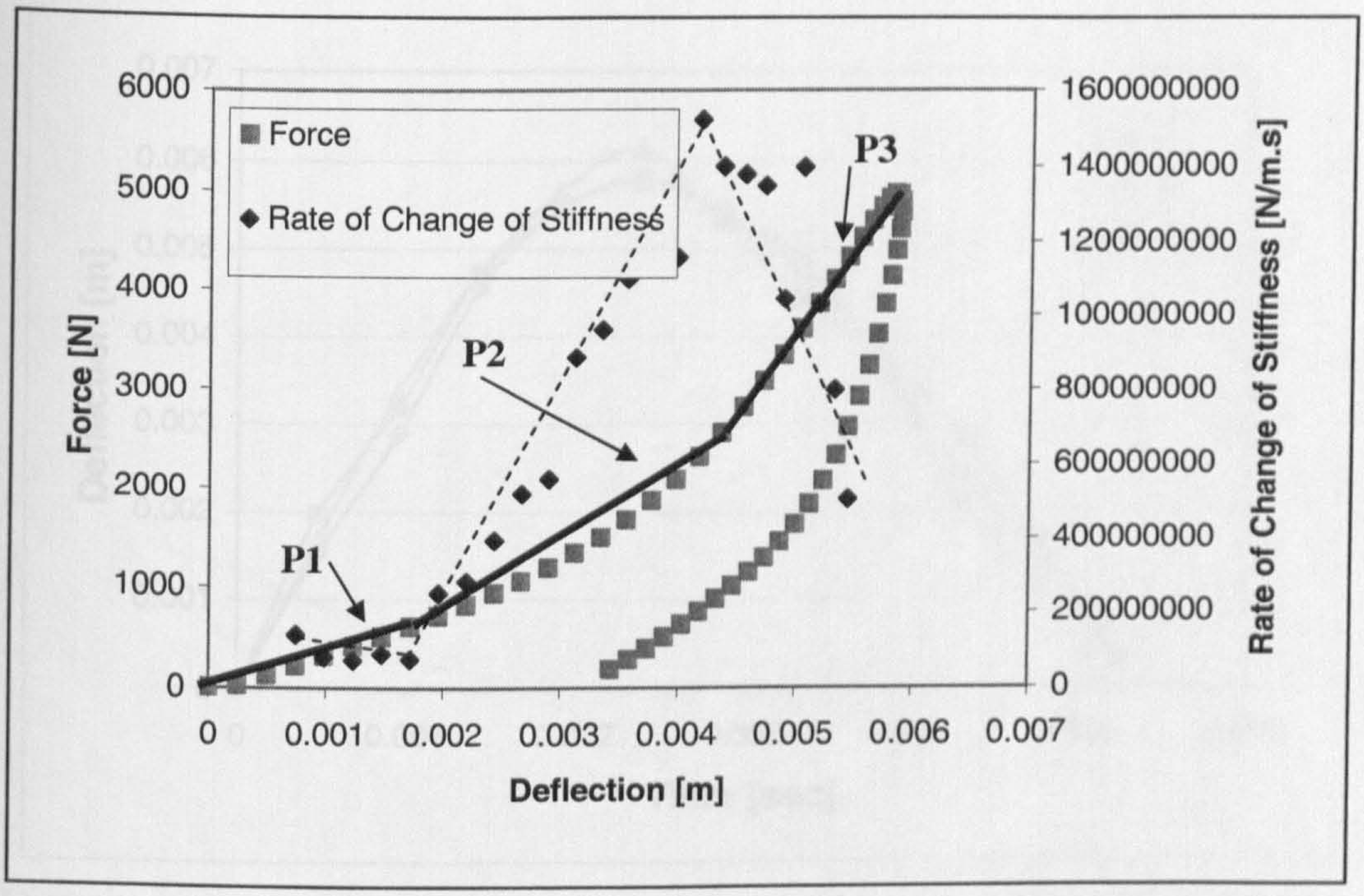


Figure 5.14: Identification of air void compression, transition and rubber compression phases of shockpad behaviour using rate of change in shockpad stiffness

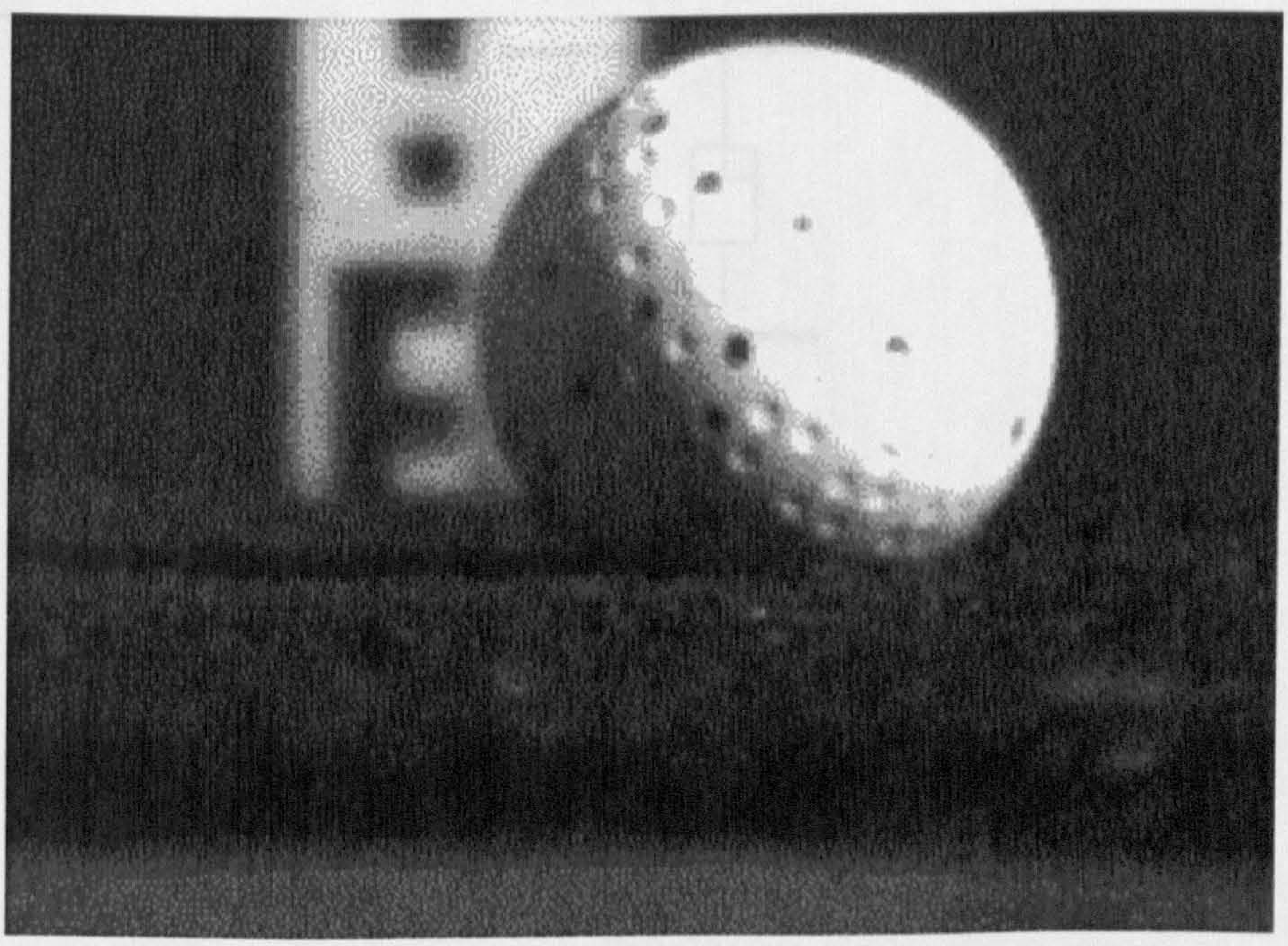


Figure 5.15: Example of a ball image taken with a high speed camera

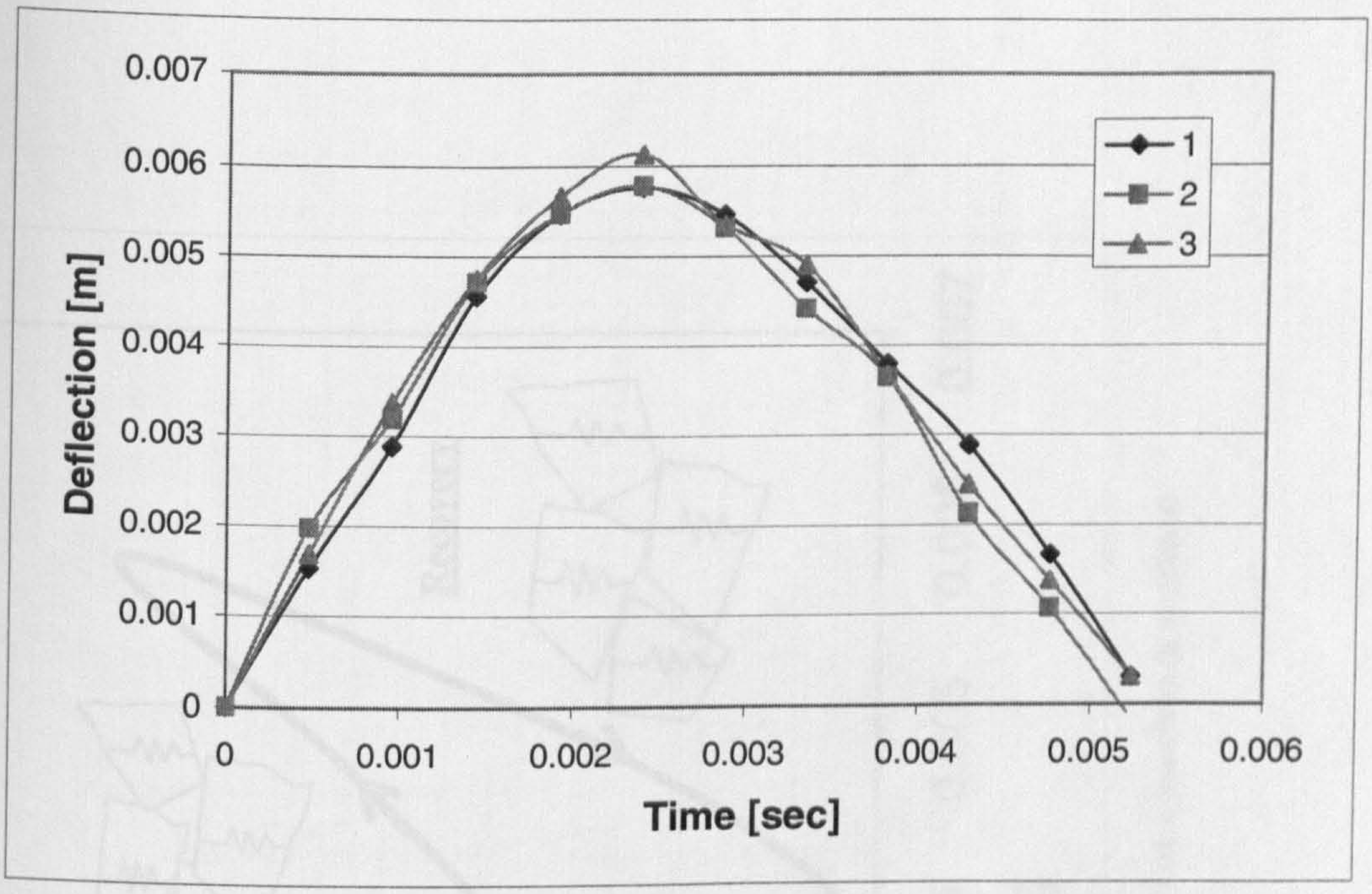


Figure 5.16: Digitising method reliability shown by three deflection measurements for the same impact

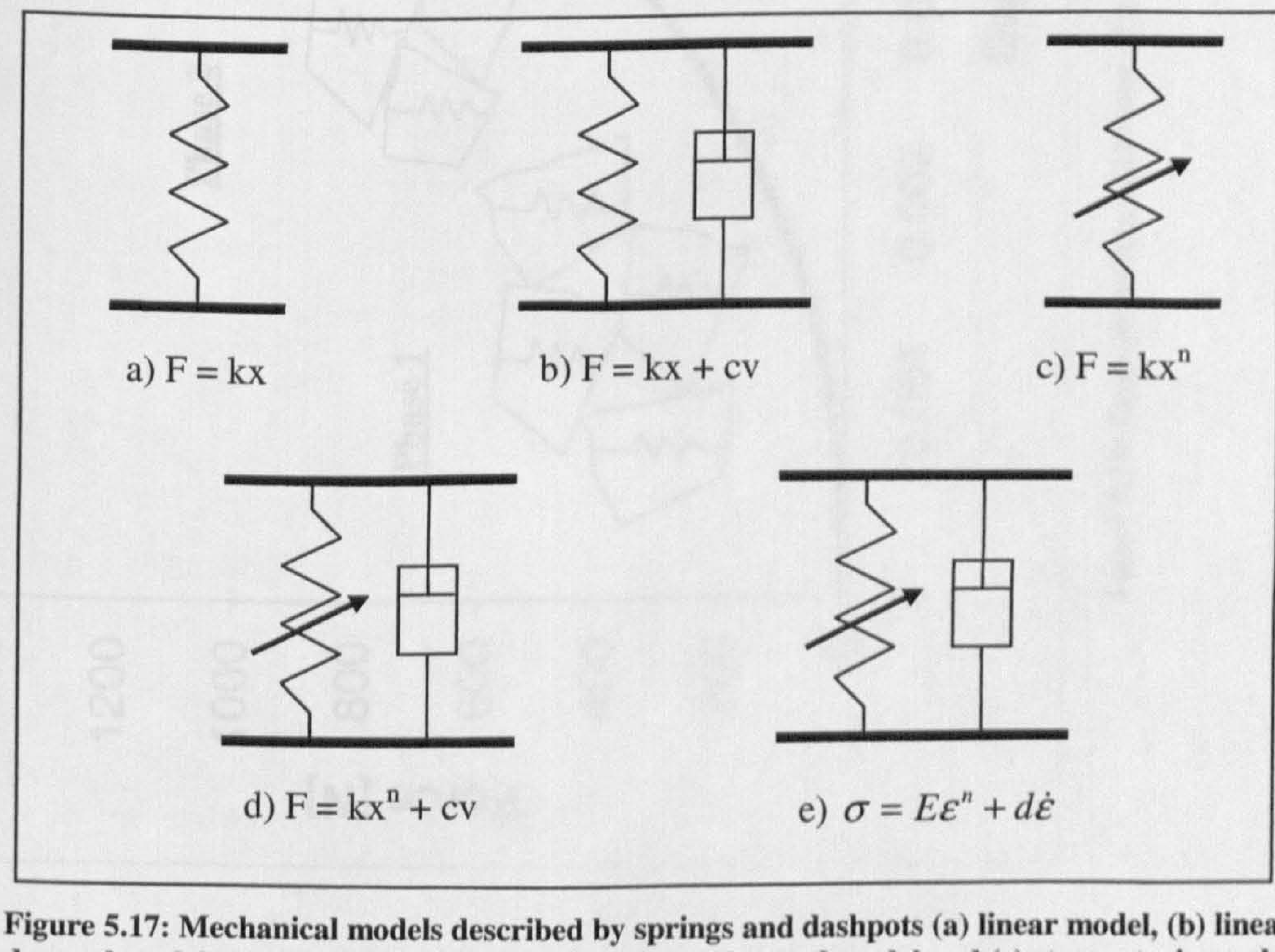


Figure 5.17: Mechanical models described by springs and dashpots (a) linear model, (b) linear damped model, (c) non-linear model, (d) non-linear damped model and (e) stress-strain model

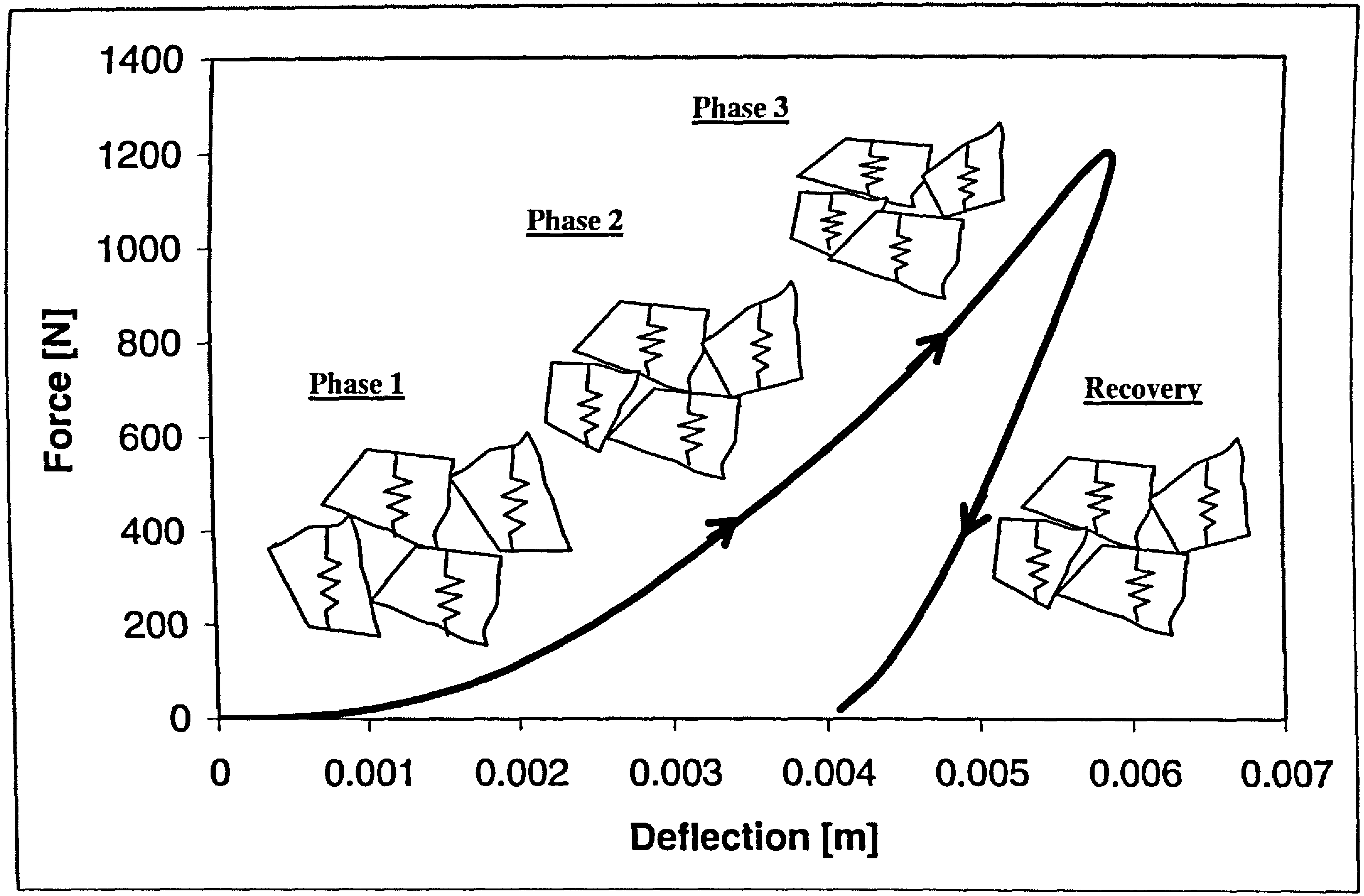


Figure 5.18: Force-deflection behaviour of a hockey ball impact on a benchmark shockpad

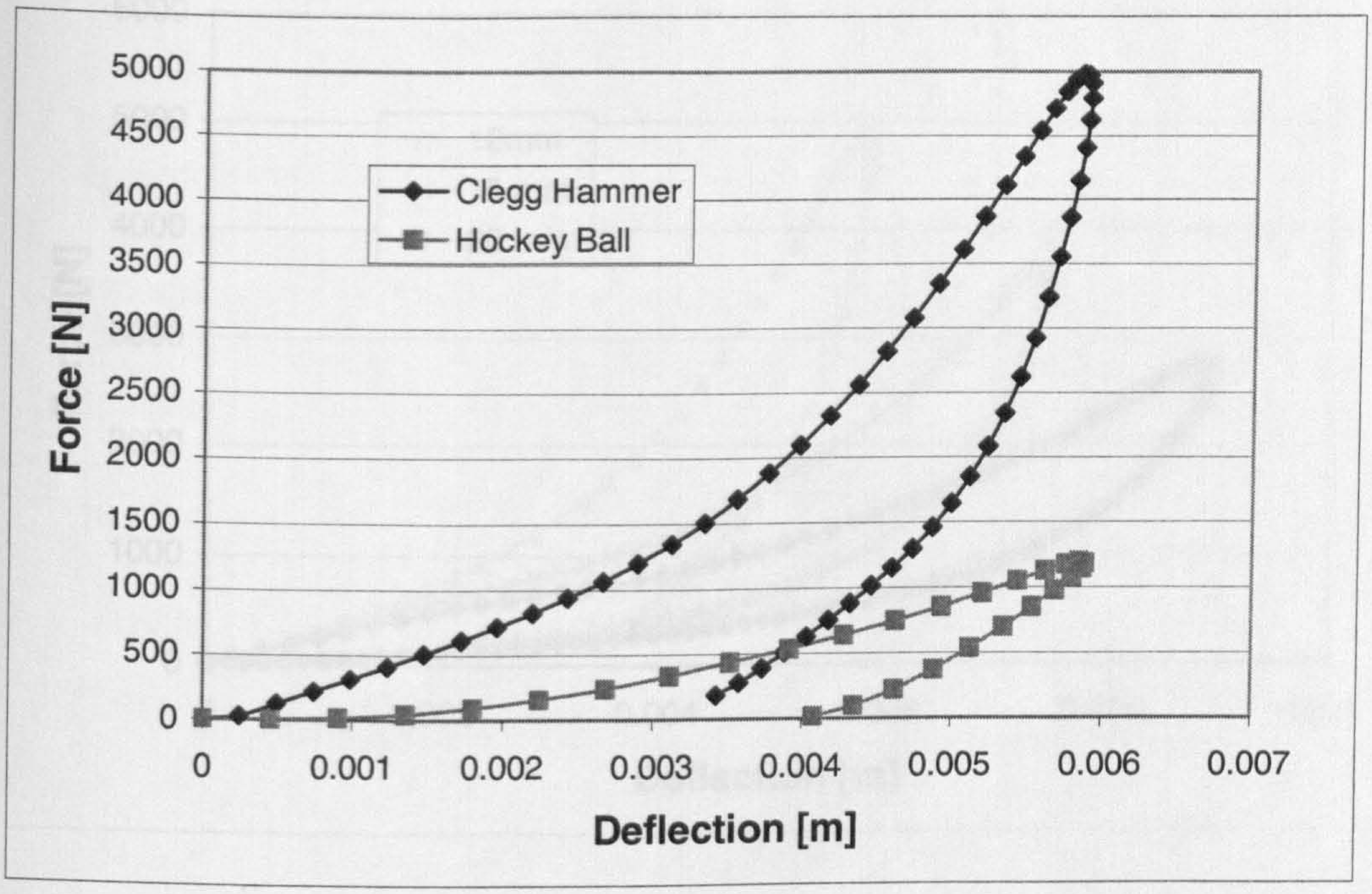


Figure 5.19: Comparison of force-deflection behaviour for Clegg Hammer and Hockey Ball impacts on a benchmark shockpad

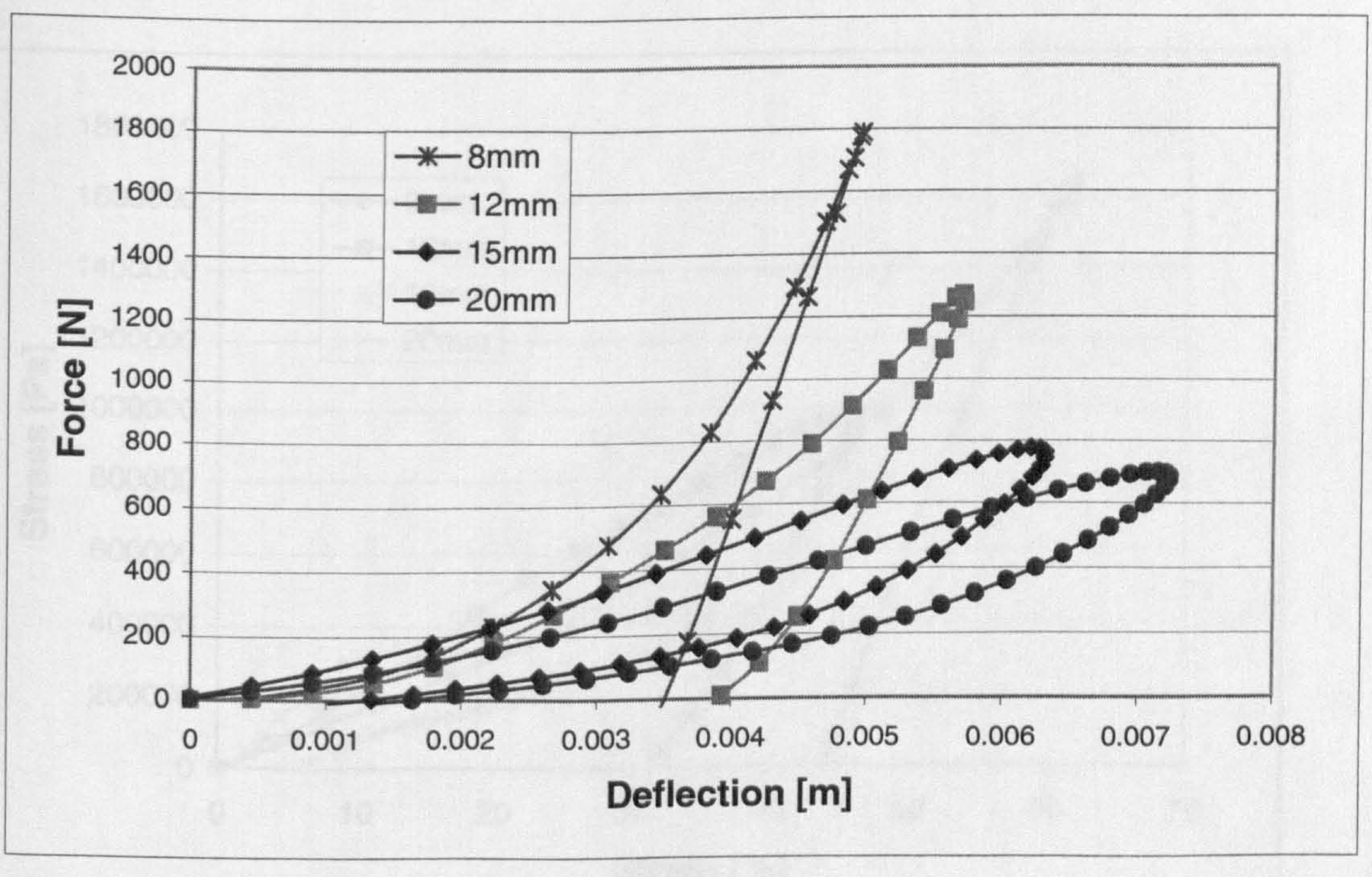


Figure 5.20: Force-deflection behaviour of hockey ball impact on shockpads of various thickness

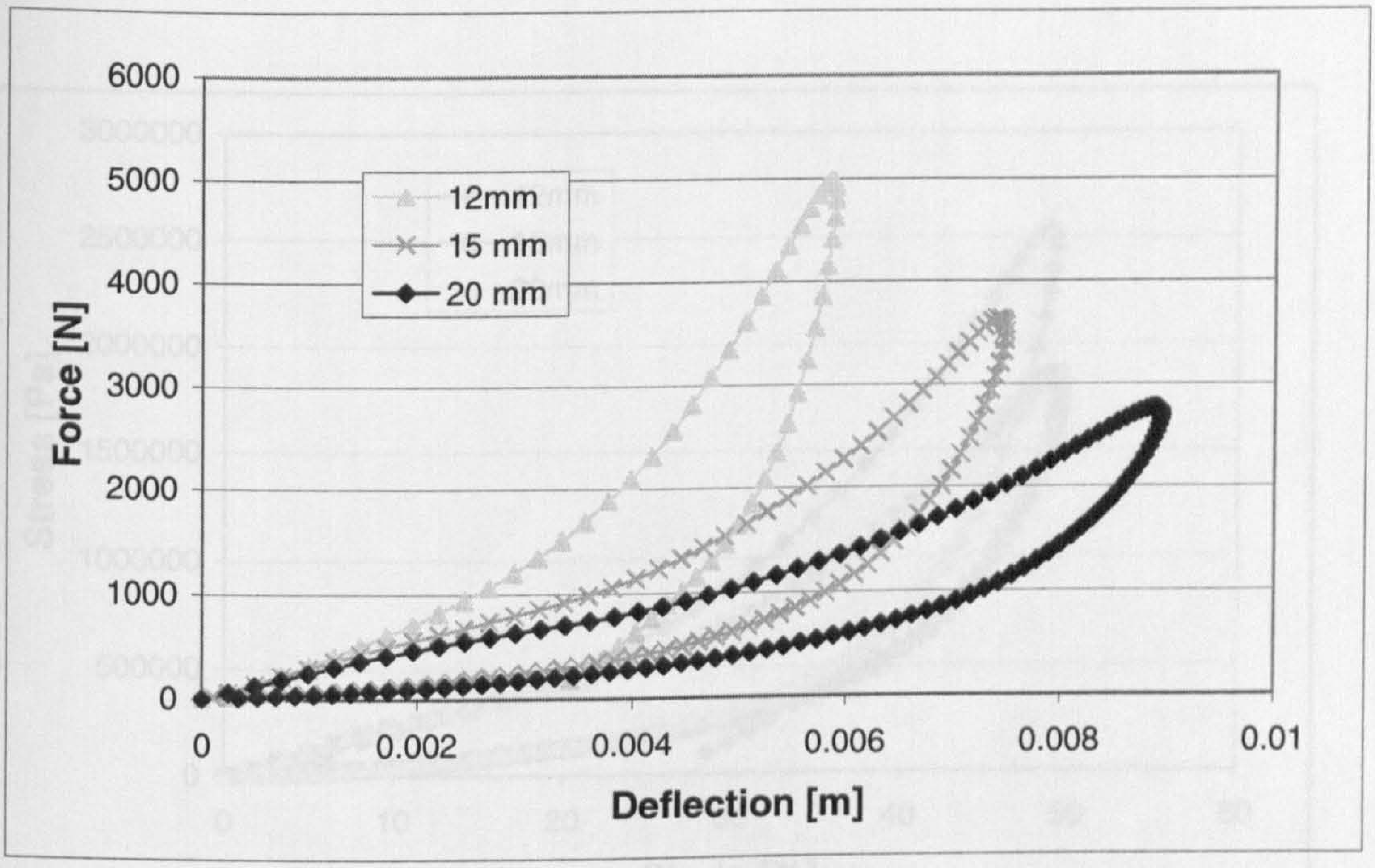


Figure 5.21: Force-deflection behaviour of Clegg Hammer impact on shockpads of various thickness

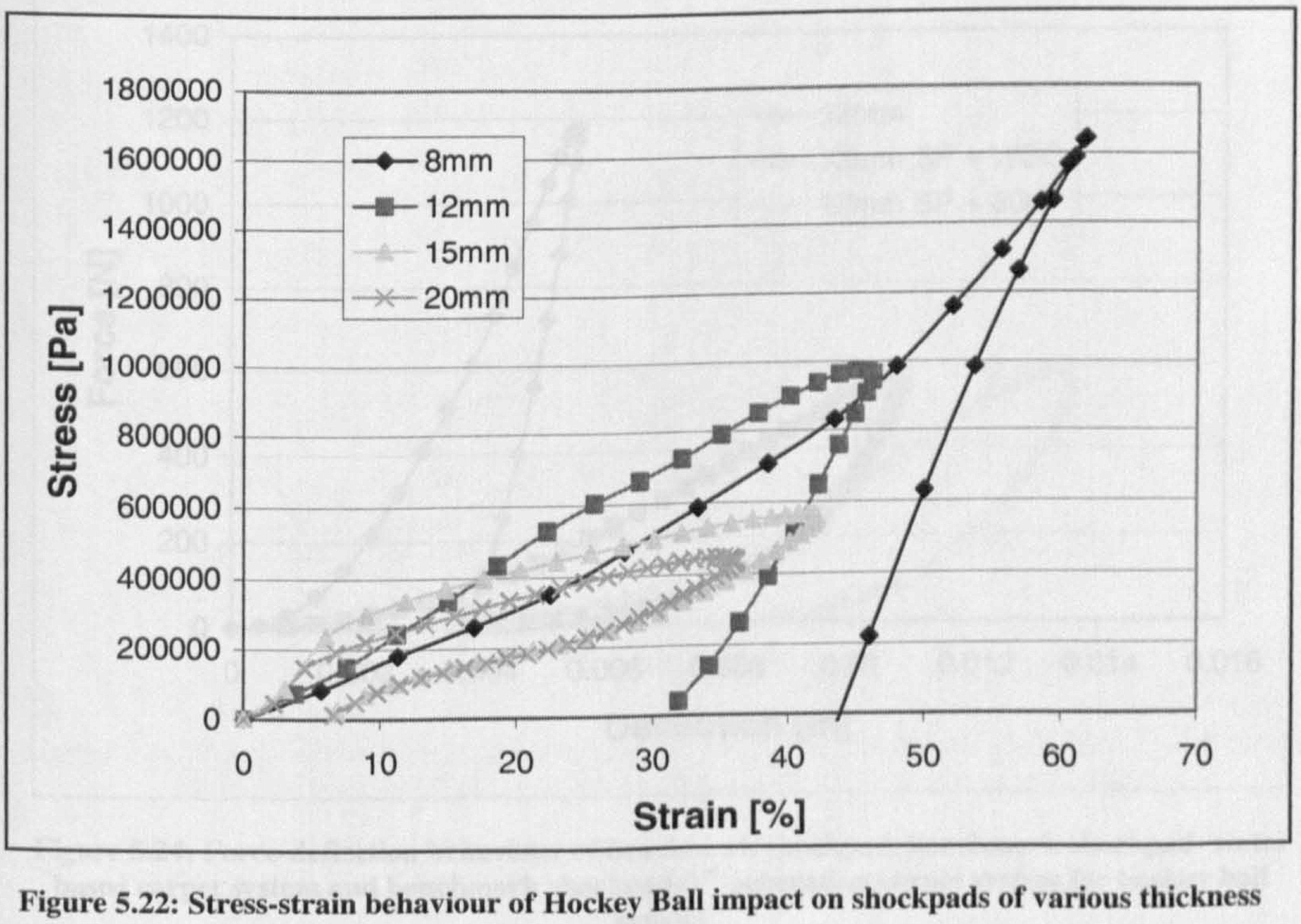


Figure 5.22: Stress-strain behaviour of Hockey Ball impact on shockpads of various thickness

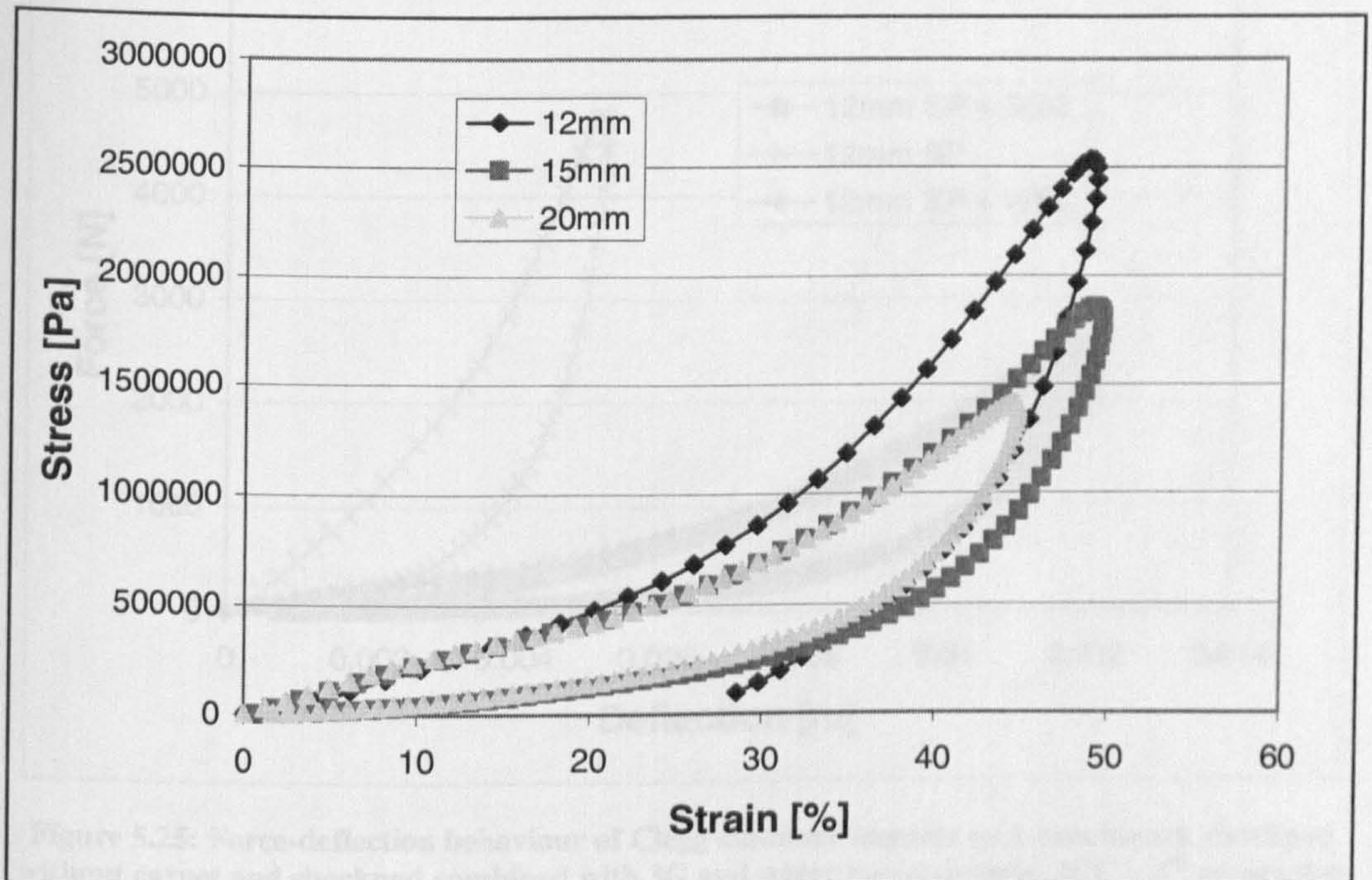


Figure 5.23: Stress-strain behaviour of Clegg Hammer impact on shockpads of various thickness

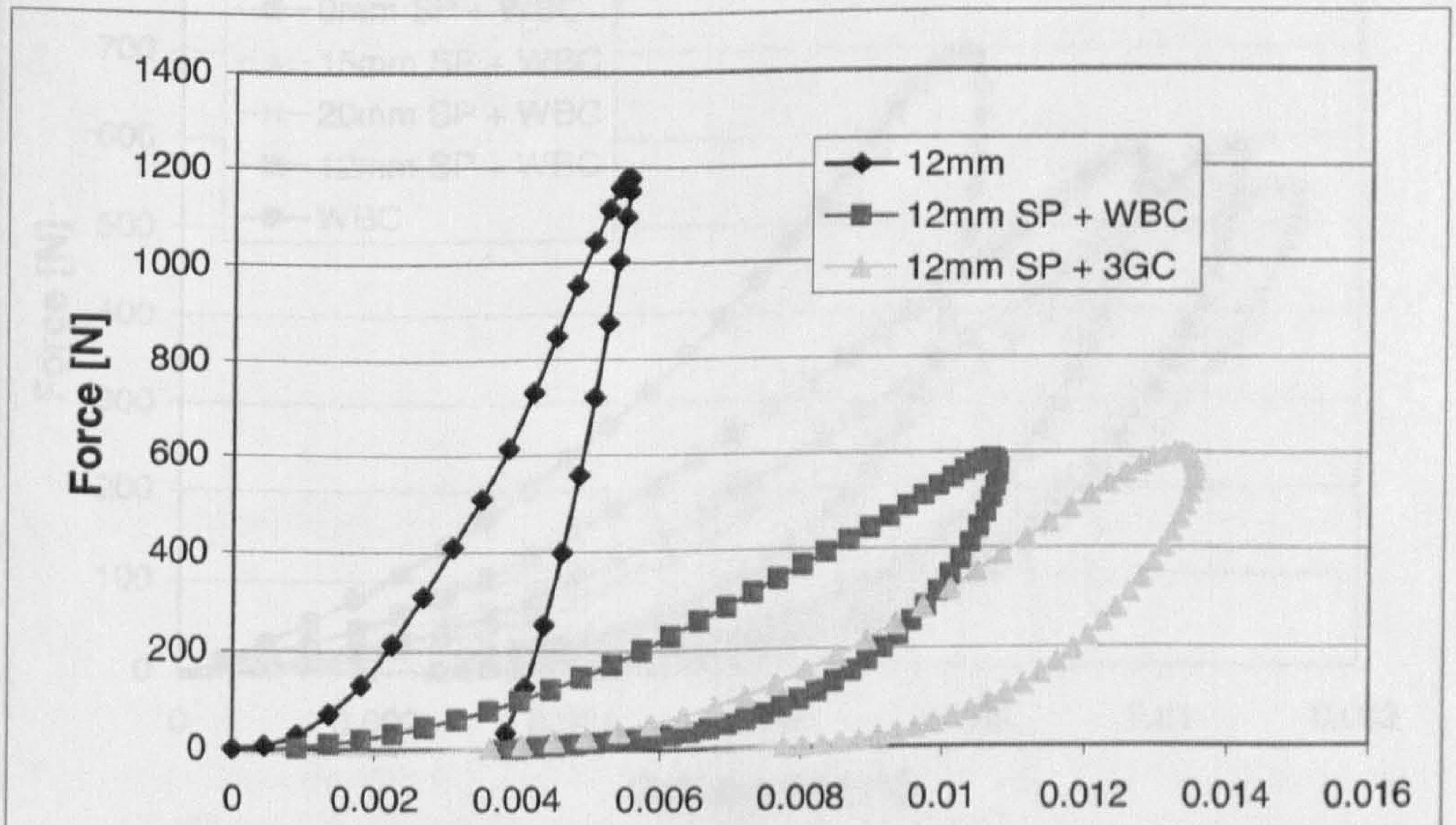


Figure 5.24: Force-deflection behaviour of benchmark shockpad, benchmark shockpad- water based carpet system and benchmark shockpad-3rd generation carpet system for hockey ball impact

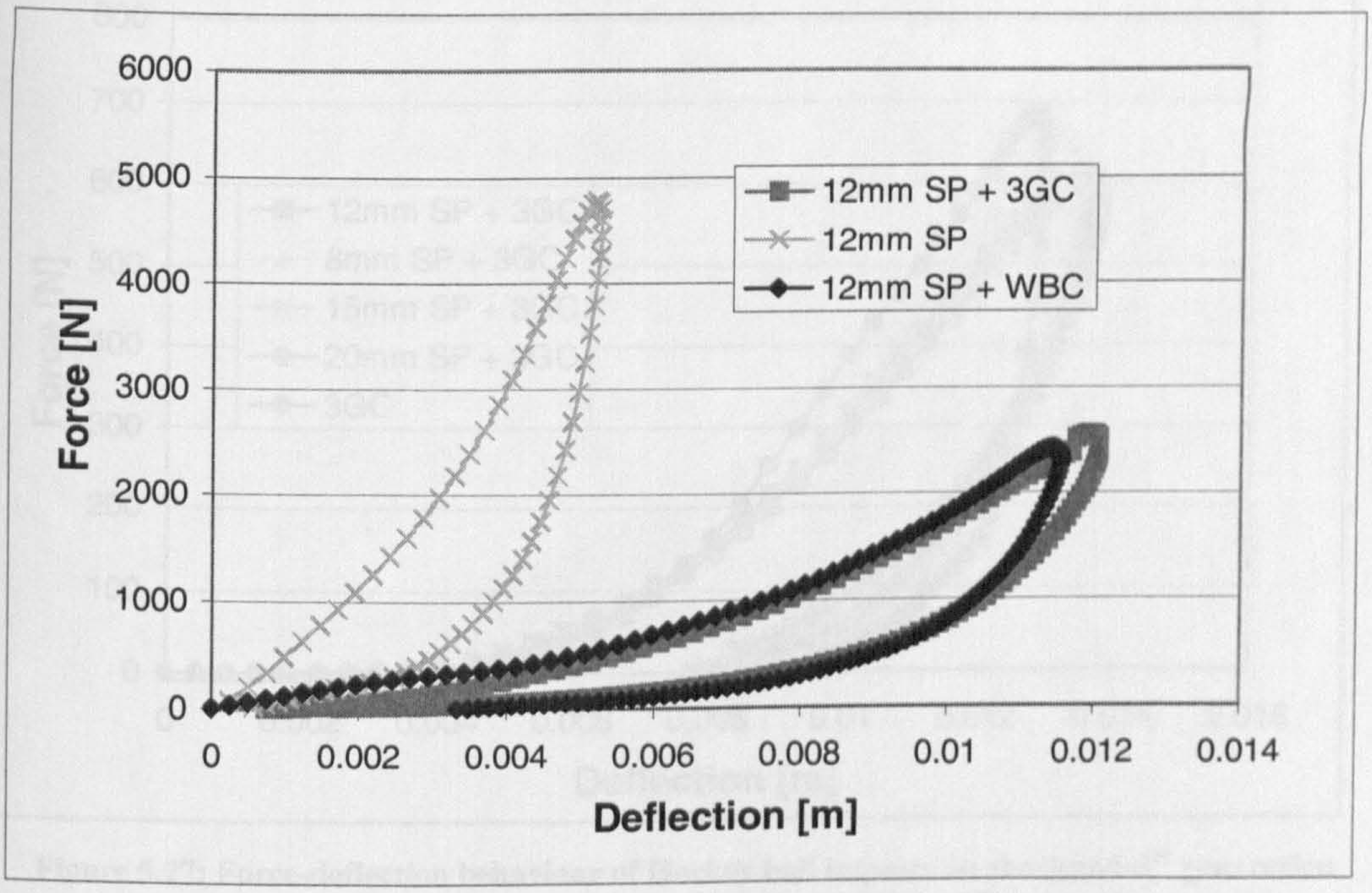


Figure 5.25: Force-deflection behaviour of Clegg Hammer impacts on a benchmark shockpad without carpet and shockpad combined with 3G and water based carpets. 3GC = 3rd generation carpet, WBC = Water based carpet

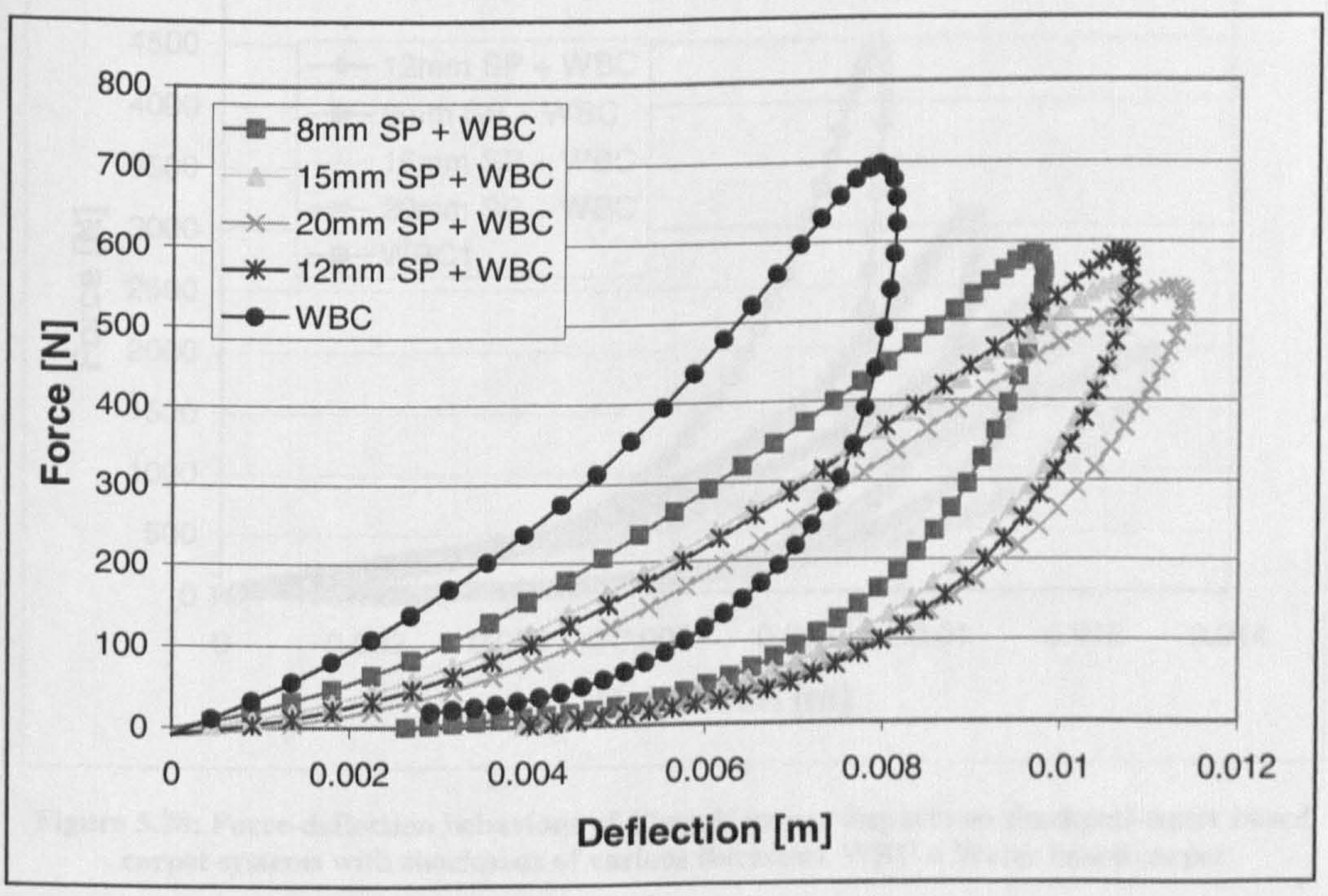


Figure 5.26: Force-deflection behaviour of Hockey ball impacts on shockpad-water based carpet systems with shockpads of various thickness. WBC = Water based carpet

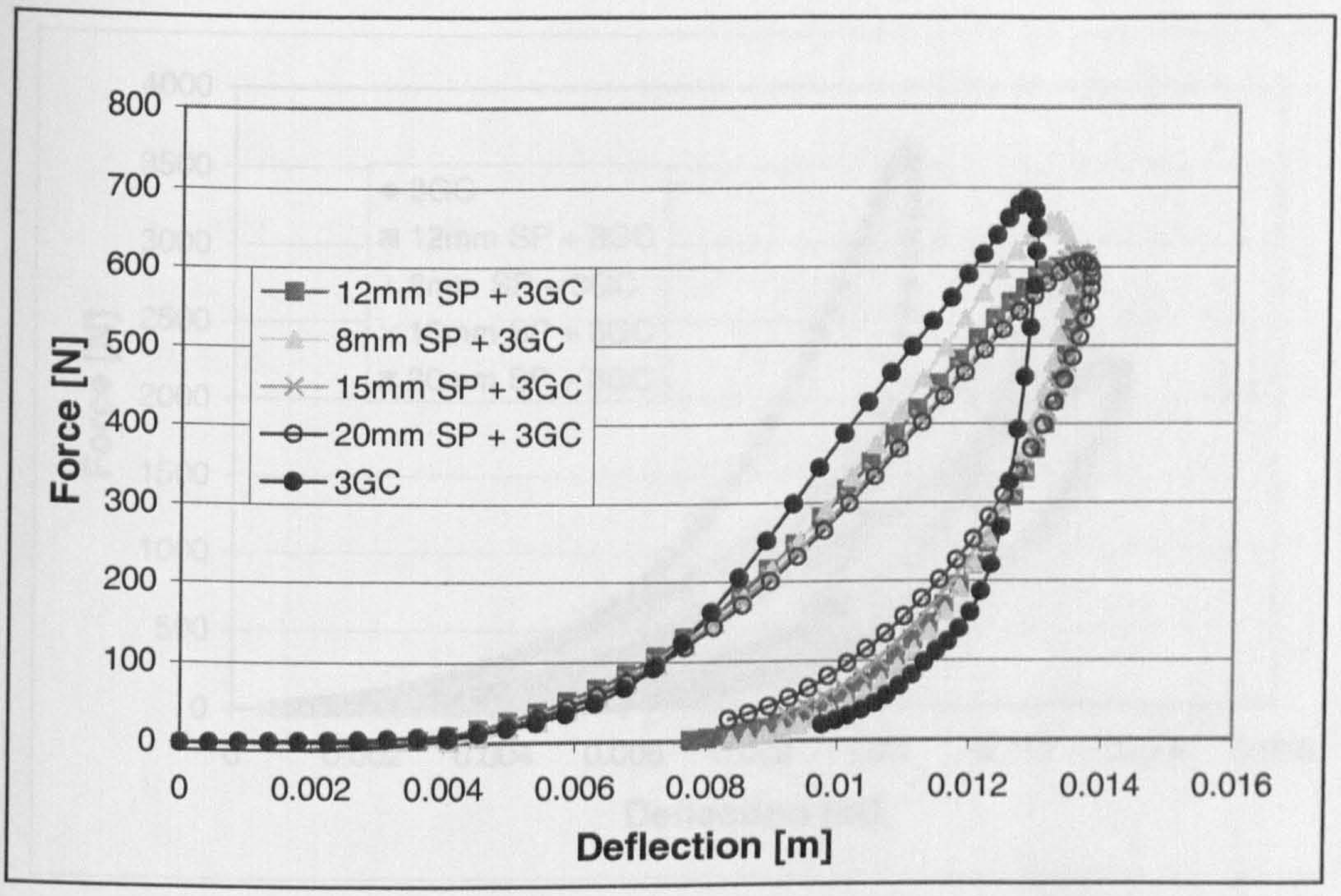


Figure 5.27: Force-deflection behaviour of Hockey ball impacts on shockpad-3rd generation carpet systems with shockpads of various thickness. 3GC = 3rd generation carpet

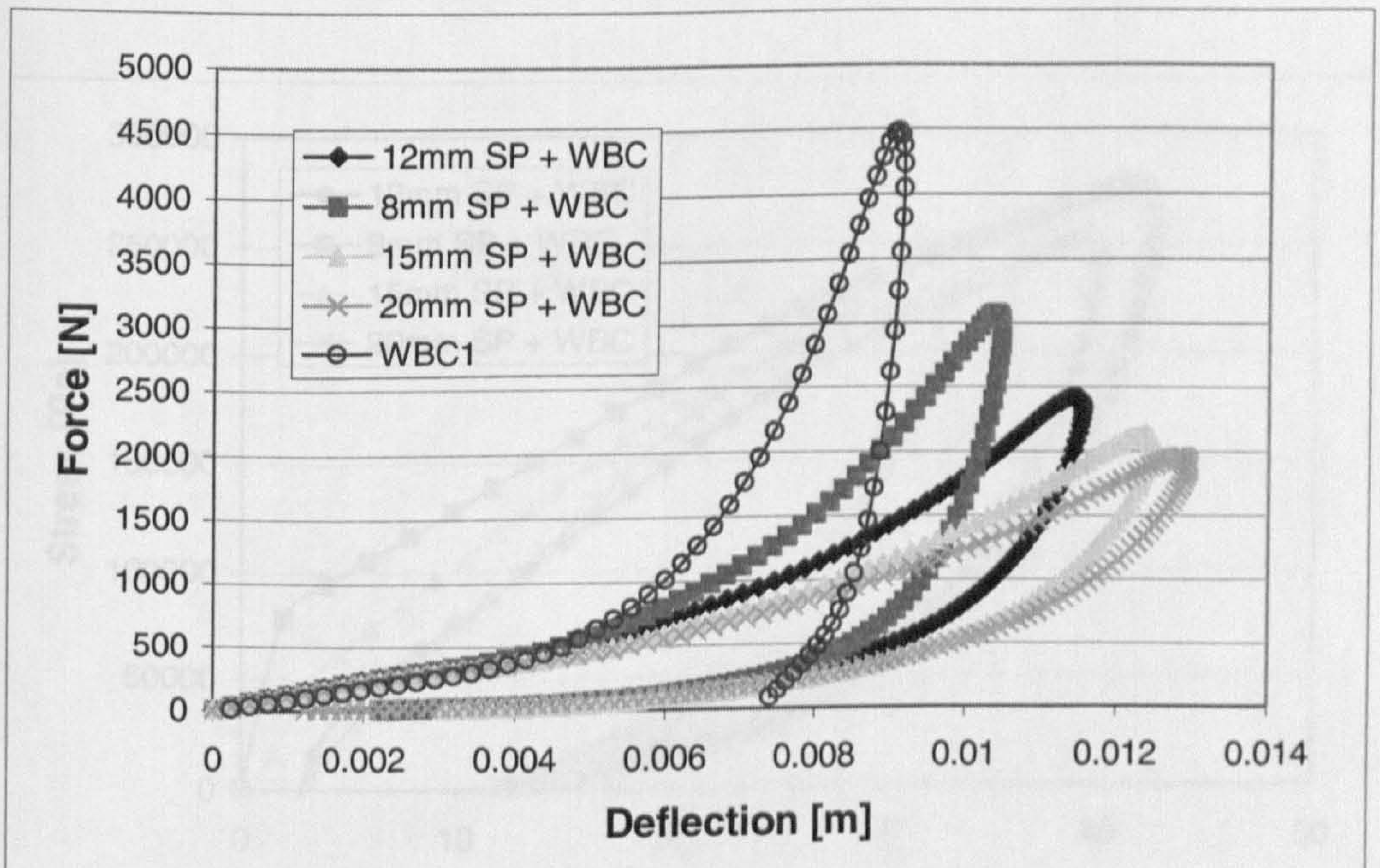


Figure 5.28: Force-deflection behaviour of Clegg Hammer impacts on shockpad-water based carpet systems with shockpads of various thickness. WBC = Water based carpet

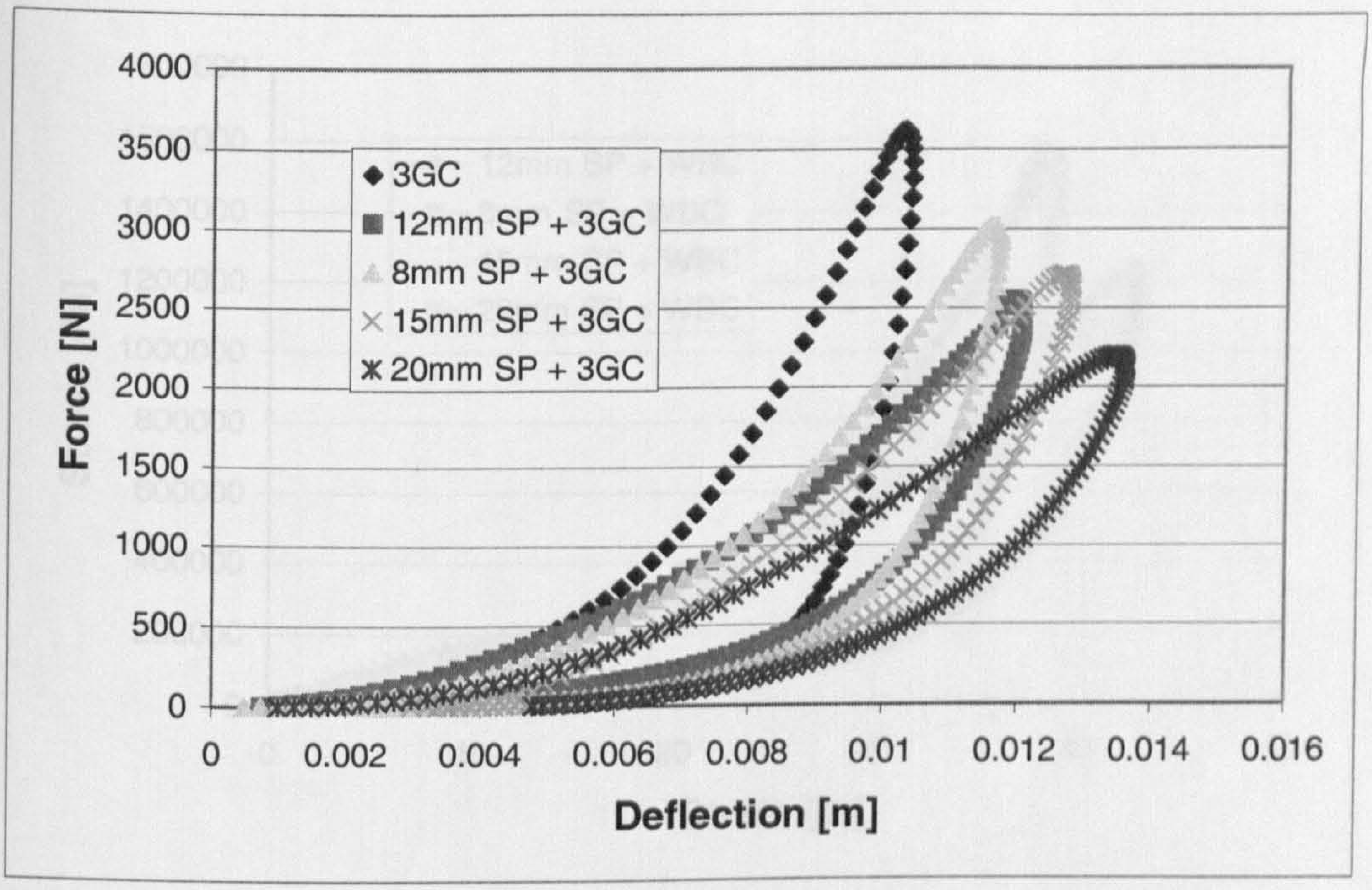


Figure 5.29: Force-deflection behaviour of Clegg Hammer impacts on shockpad-3rd generation carpet systems with shockpads of various thickness. 3GC = 3rd generation carpet

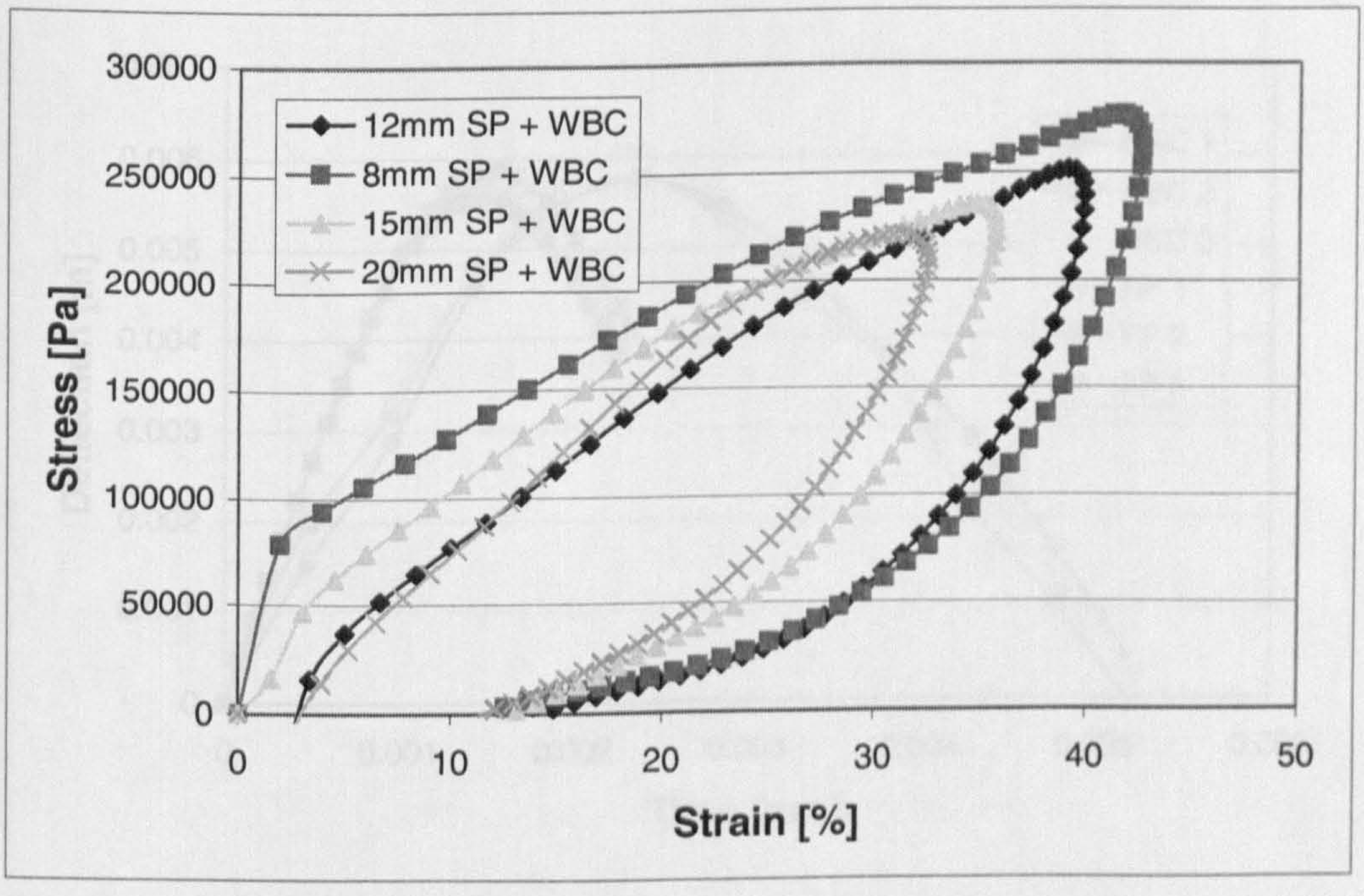


Figure 5.30: Stress-strain behaviour of hockey ball impacts on shockpad-water based carpet systems with shockpads of various thickness. WBC = Water based carpet

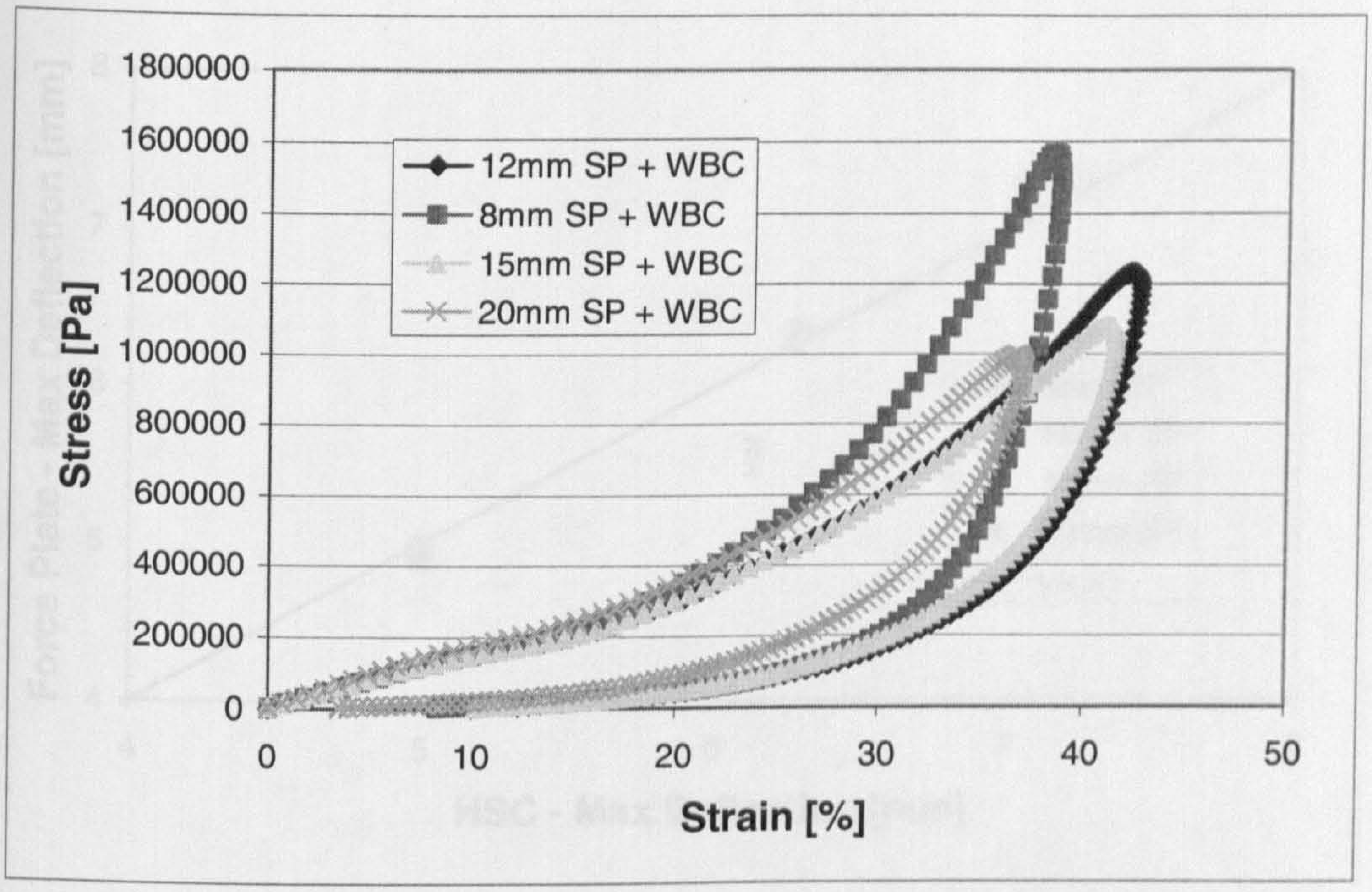


Figure 5.31: Stress-strain behaviour of Clegg Hammer Impacts on shockpad- water based carpet systems with shockpads of various thickness. WBC = Water based carpet

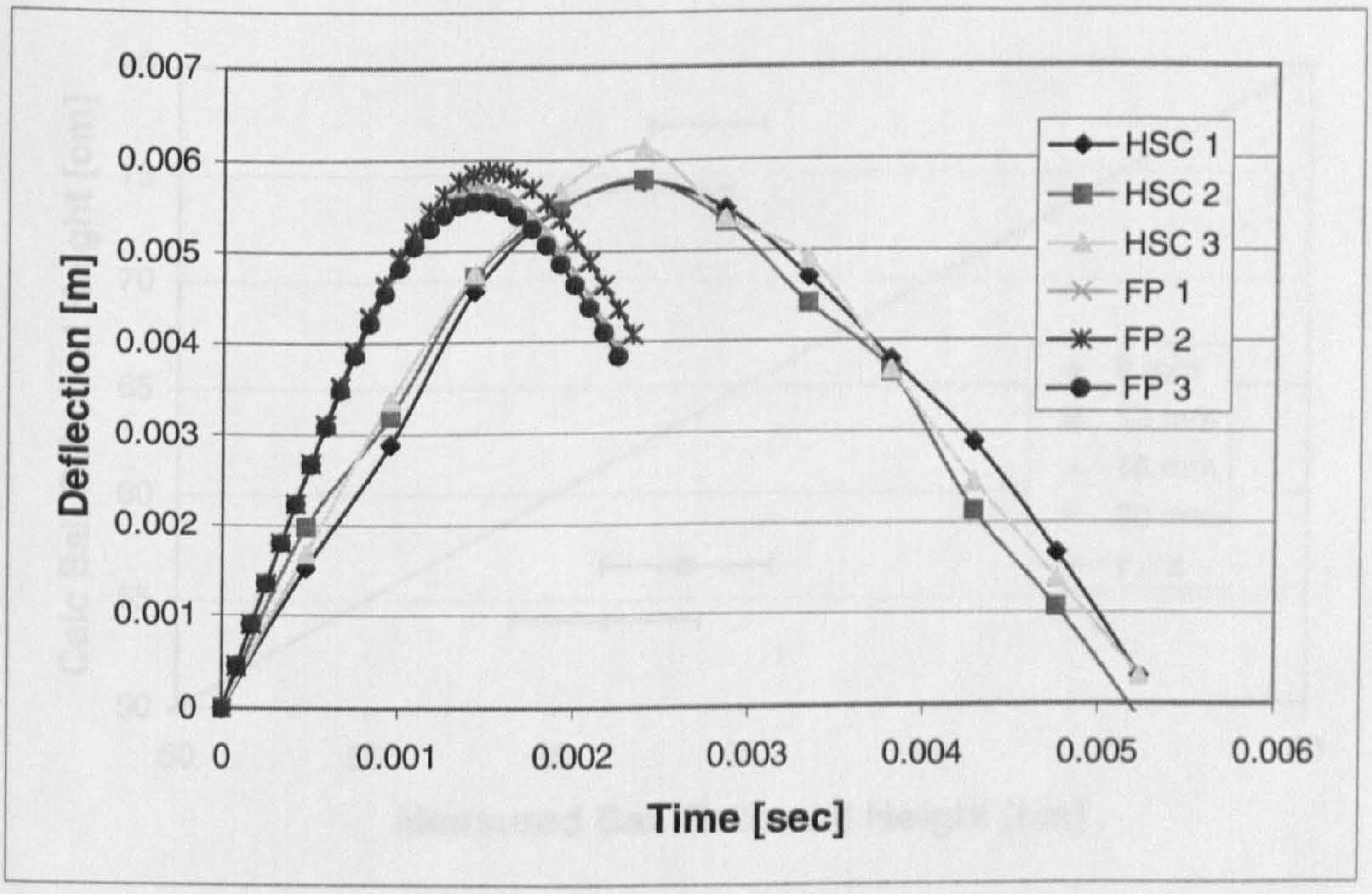


Figure 5.32: Comparison of deflection-time behaviour for high speed camera images and force plate data calculations for a benchmark shockpad

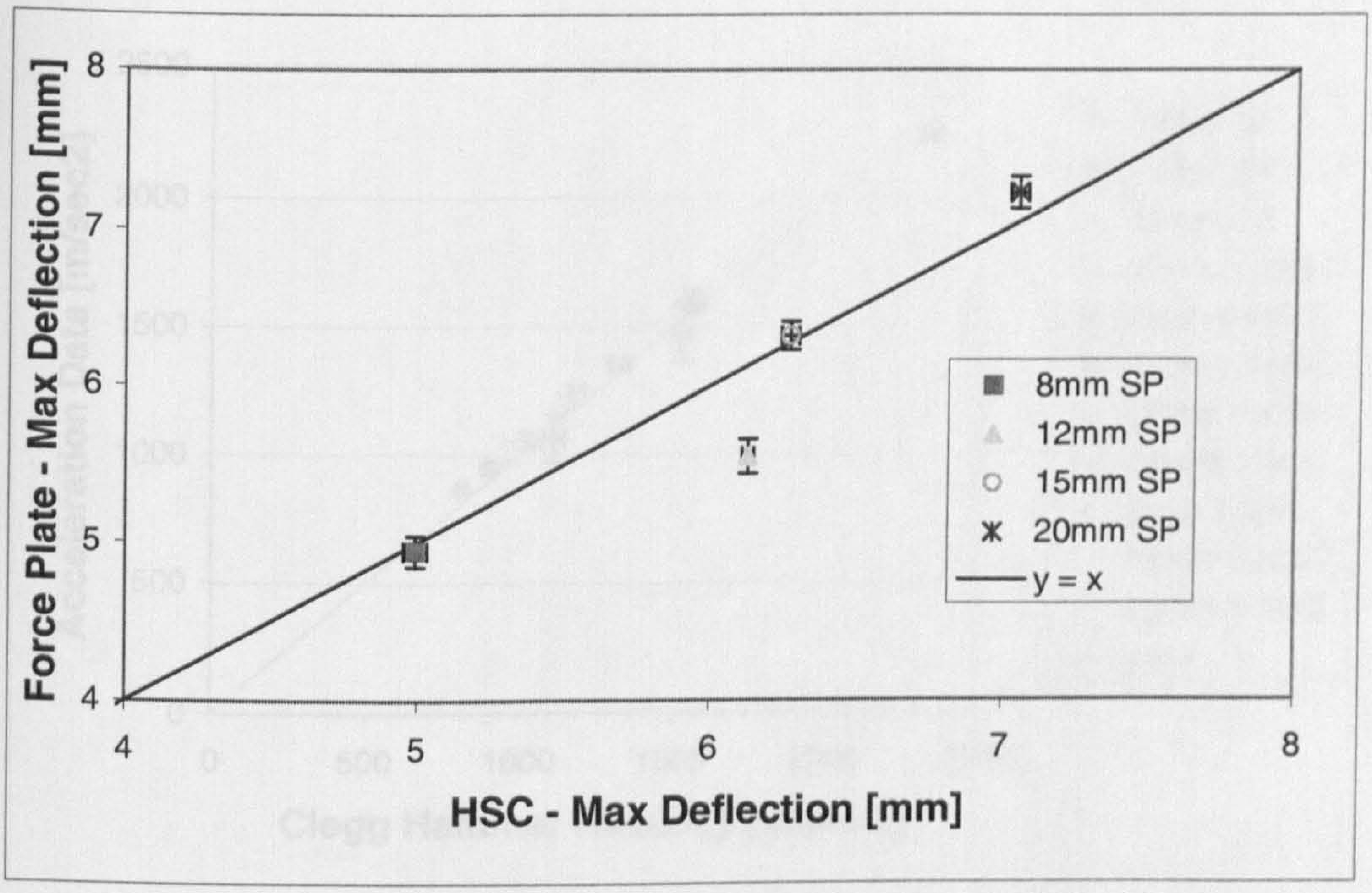


Figure 5.33: Comparison of maximum ball deflection from force plate data and high speed camera images

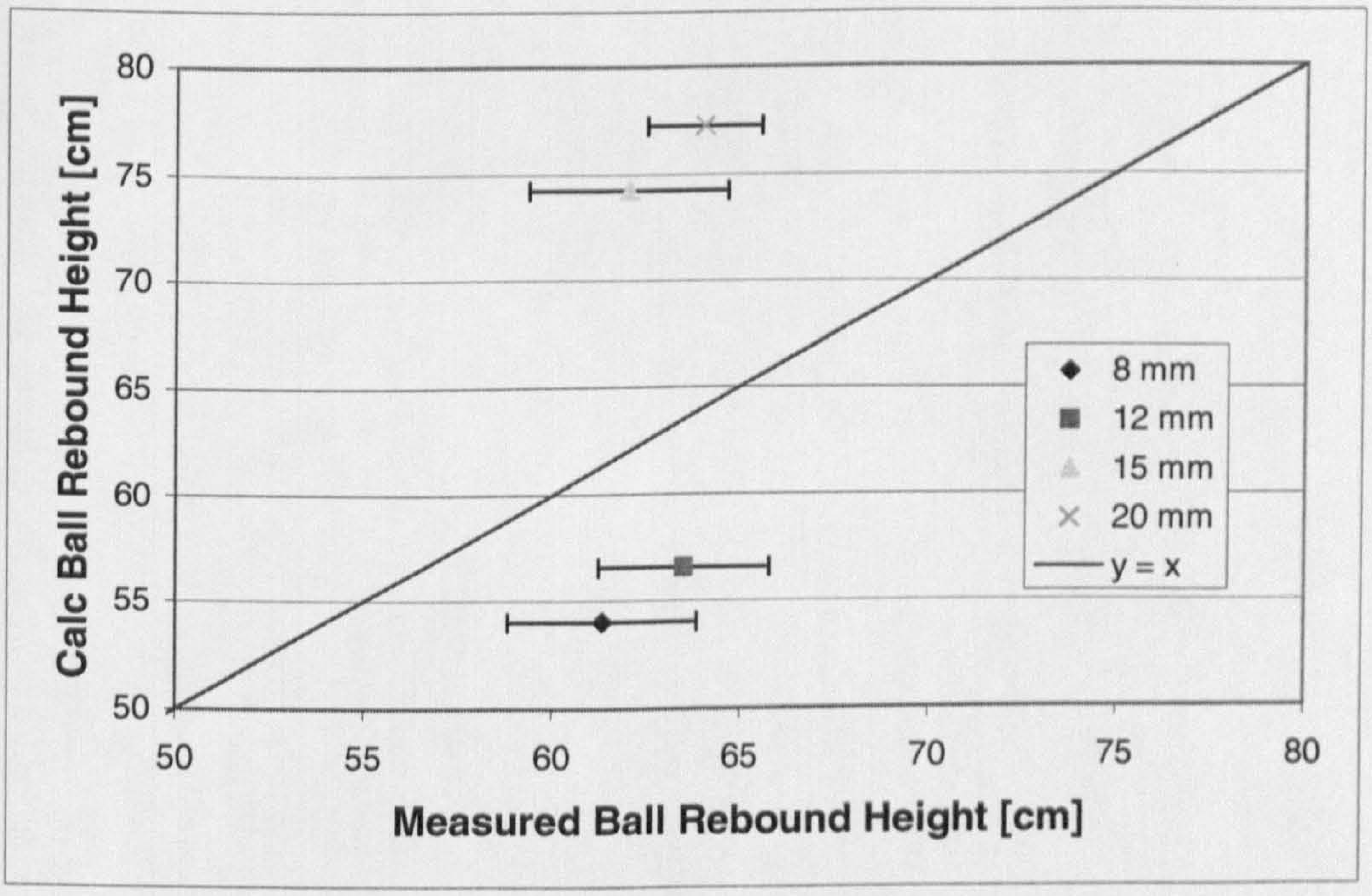


Figure 5.34: Comparison of ball rebound heights predicted from force plate data and measured rebound height

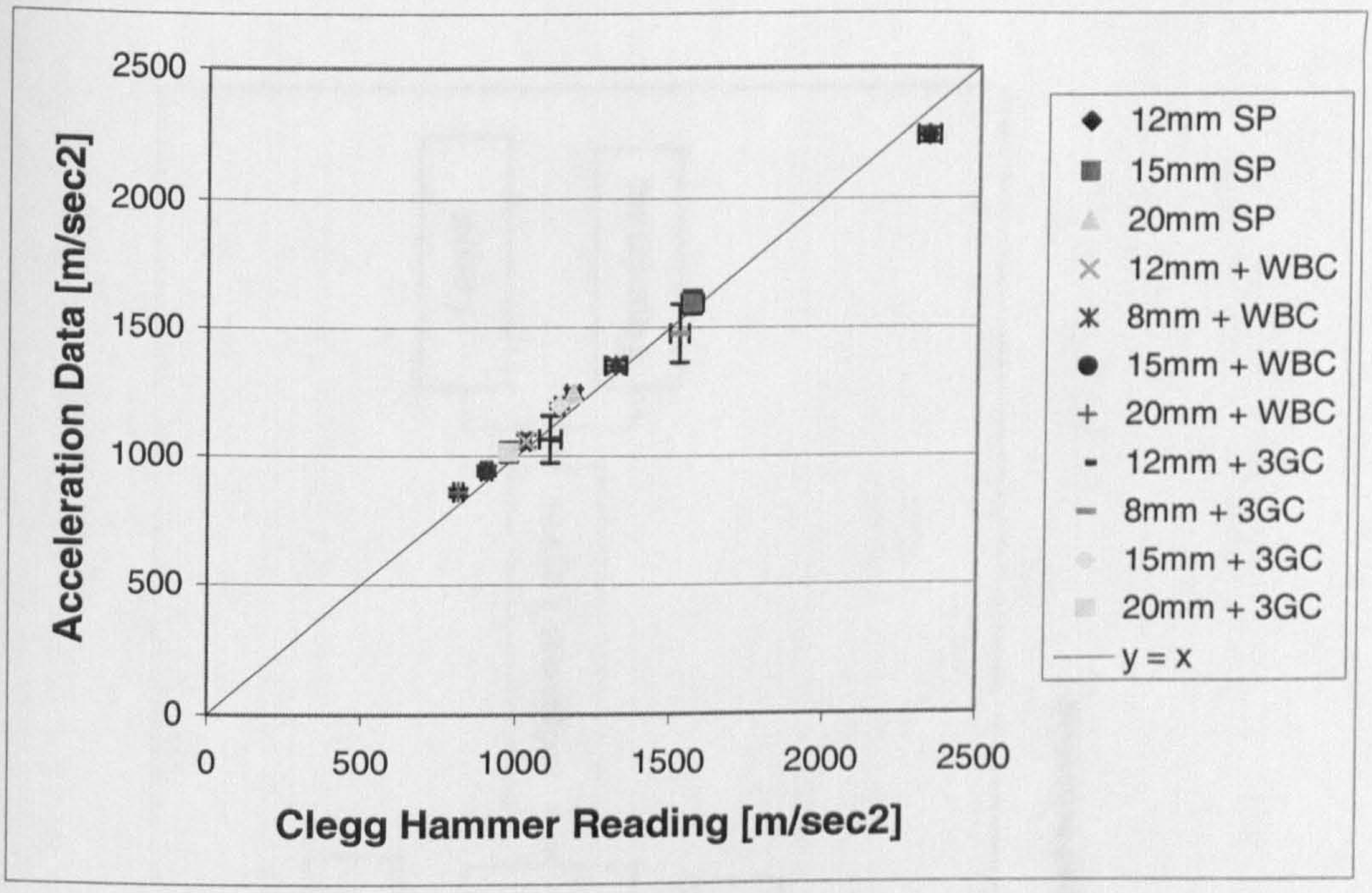


Figure 5.35: Comparison of acceleration data with Clegg impact values

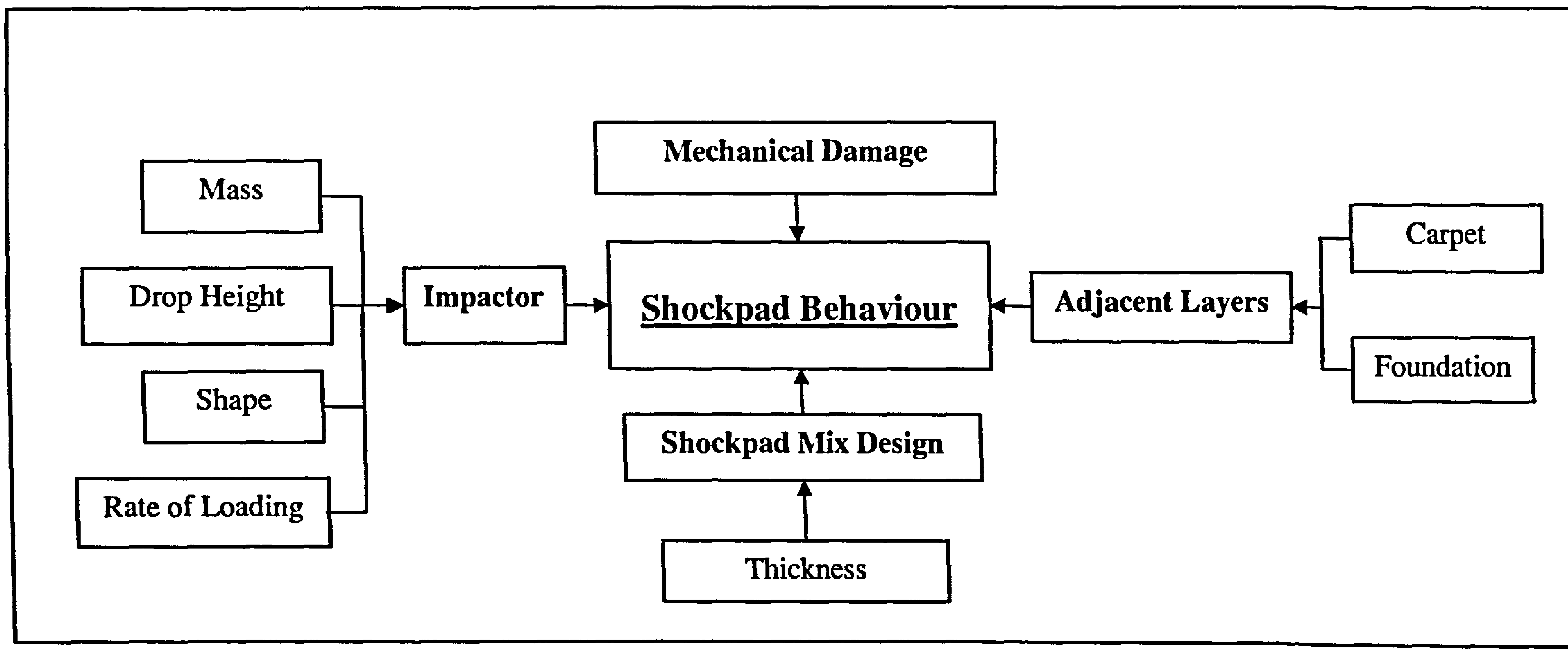
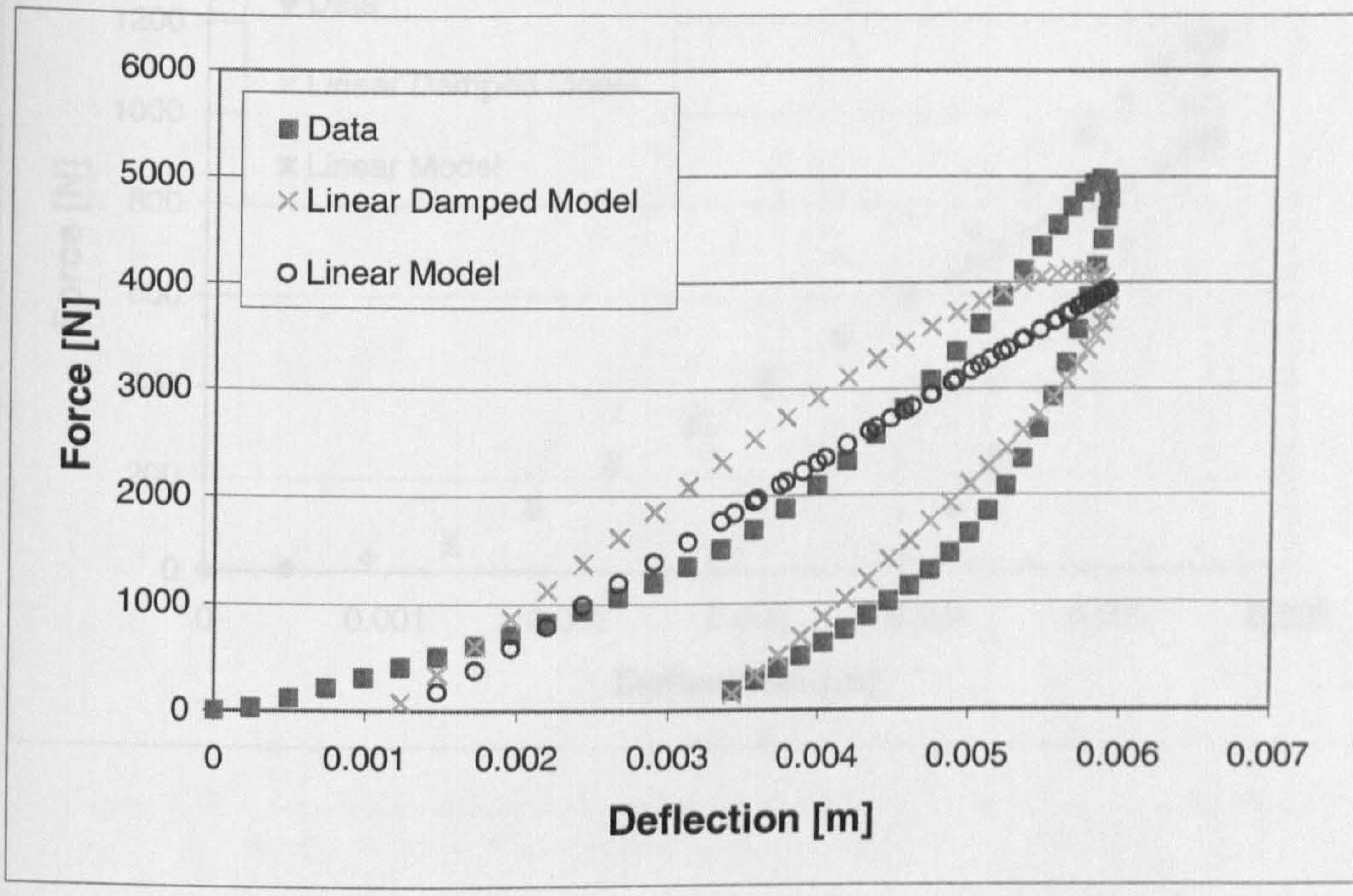


Figure 5.36: Diagram of factors affecting shockpad behaviour



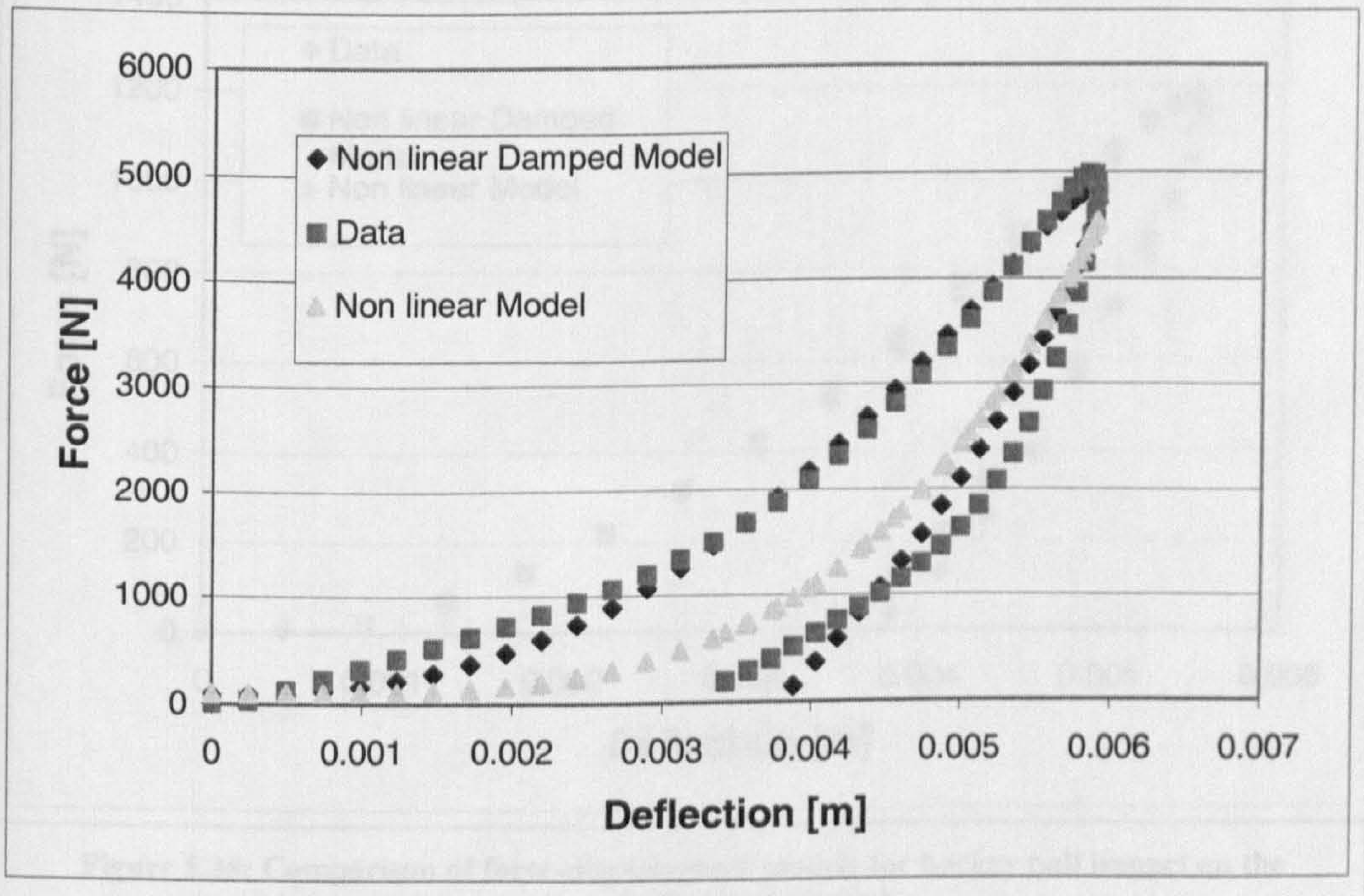


Figure 5.37: Comparison of force-displacement models for Clegg Hammer impacts on the benchmark 12 mm shockpad

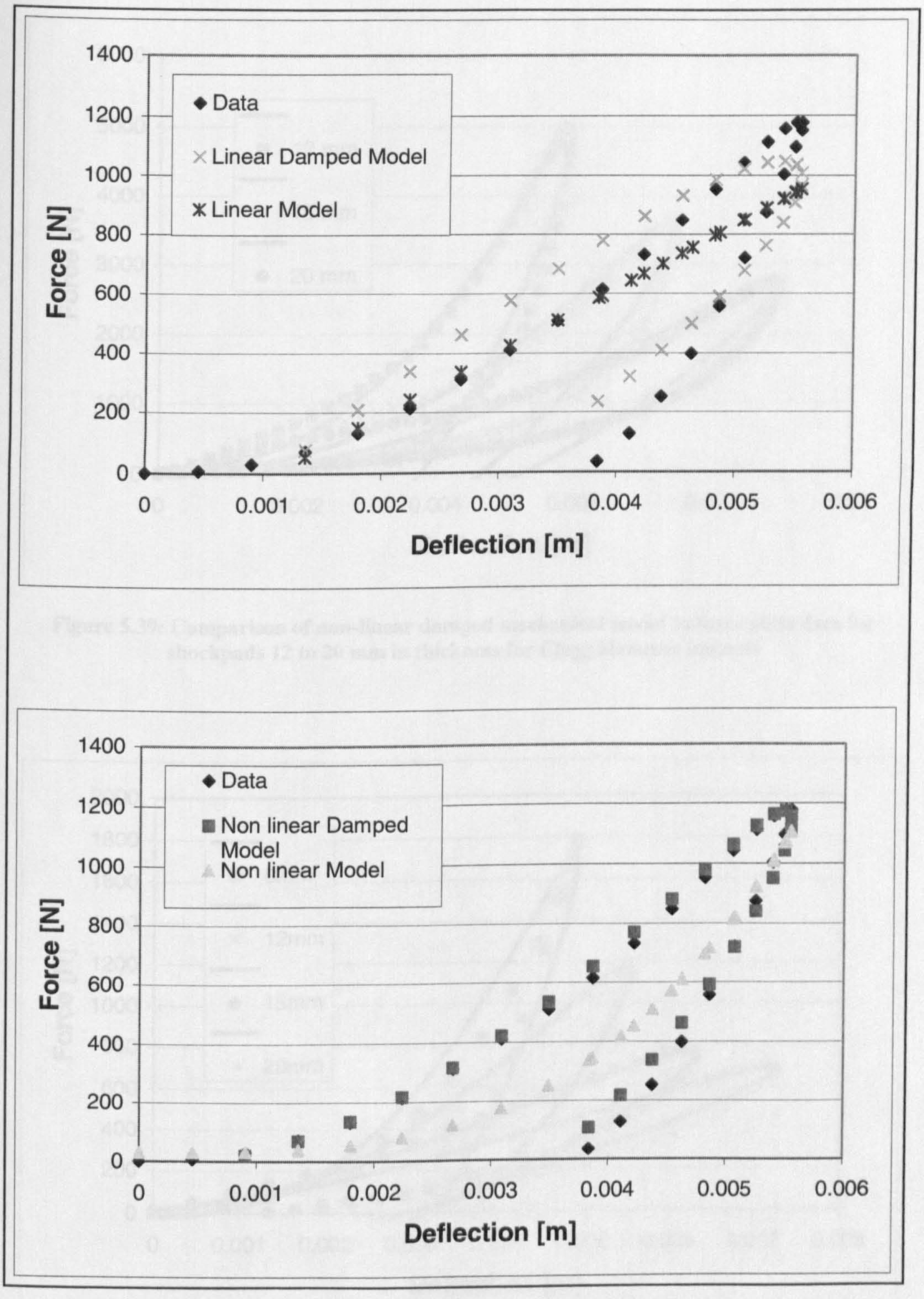


Figure 5.38: Comparison of force-displacement models for hockey ball impact on the benchmark 12 mm shockpad

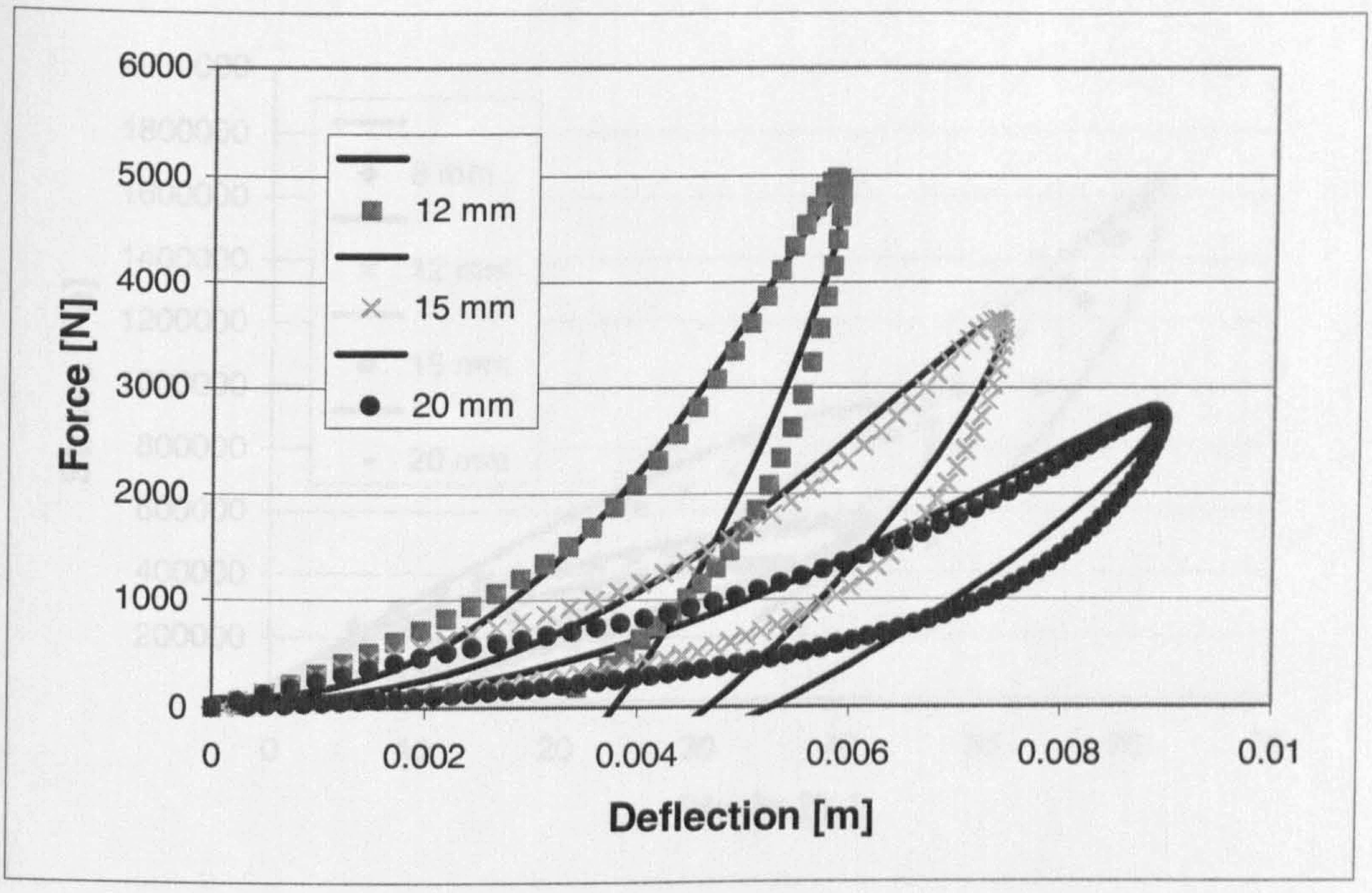


Figure 5.39: Comparison of non-linear damped mechanical model to force plate data for shockpads 12 to 20 mm in thickness for Clegg Hammer impacts

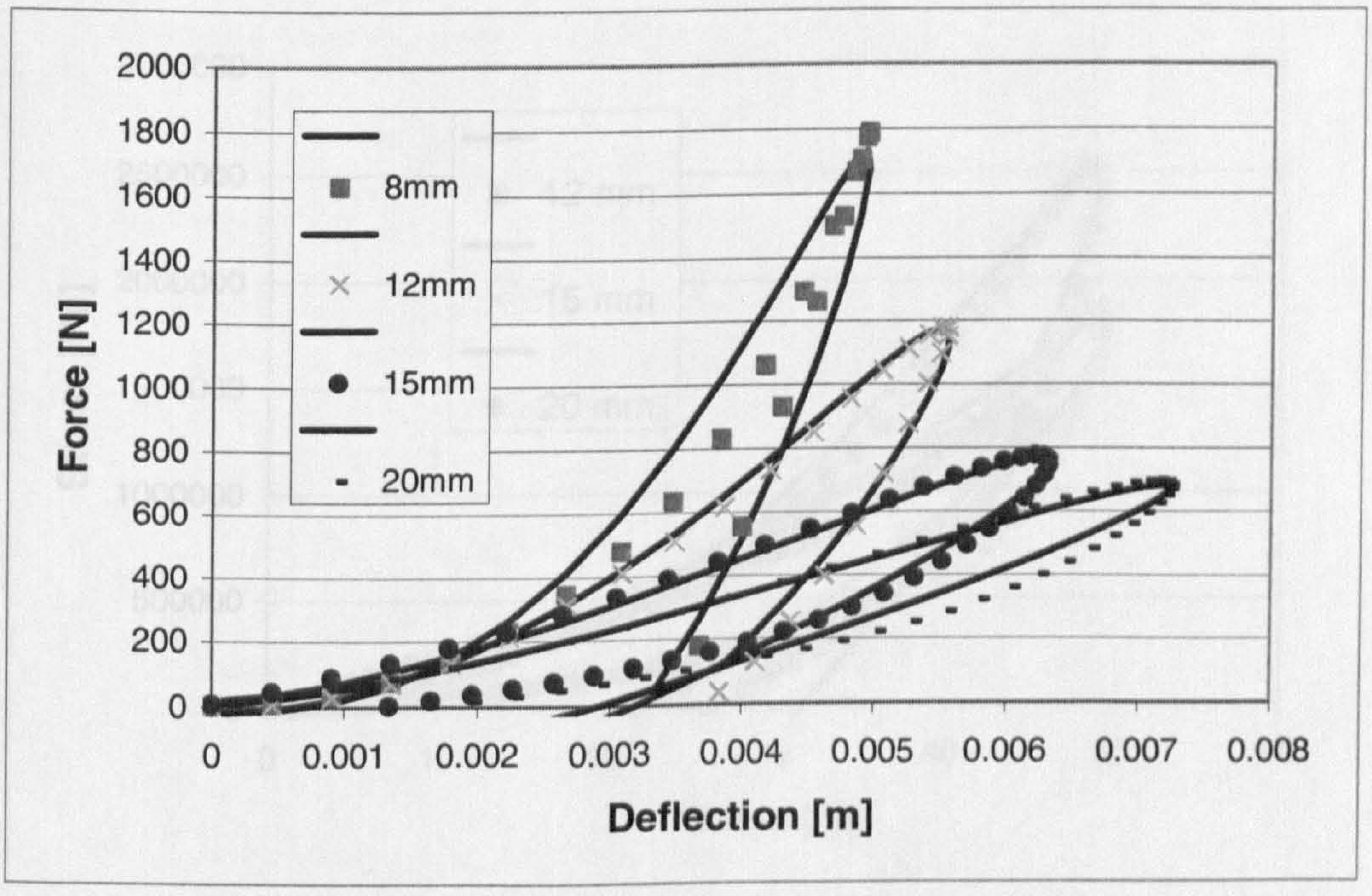


Figure 5.40: Comparison of non-linear damped mechanical model to force plate data for shockpads 8 to 20 mm in thickness for hockey ball impacts

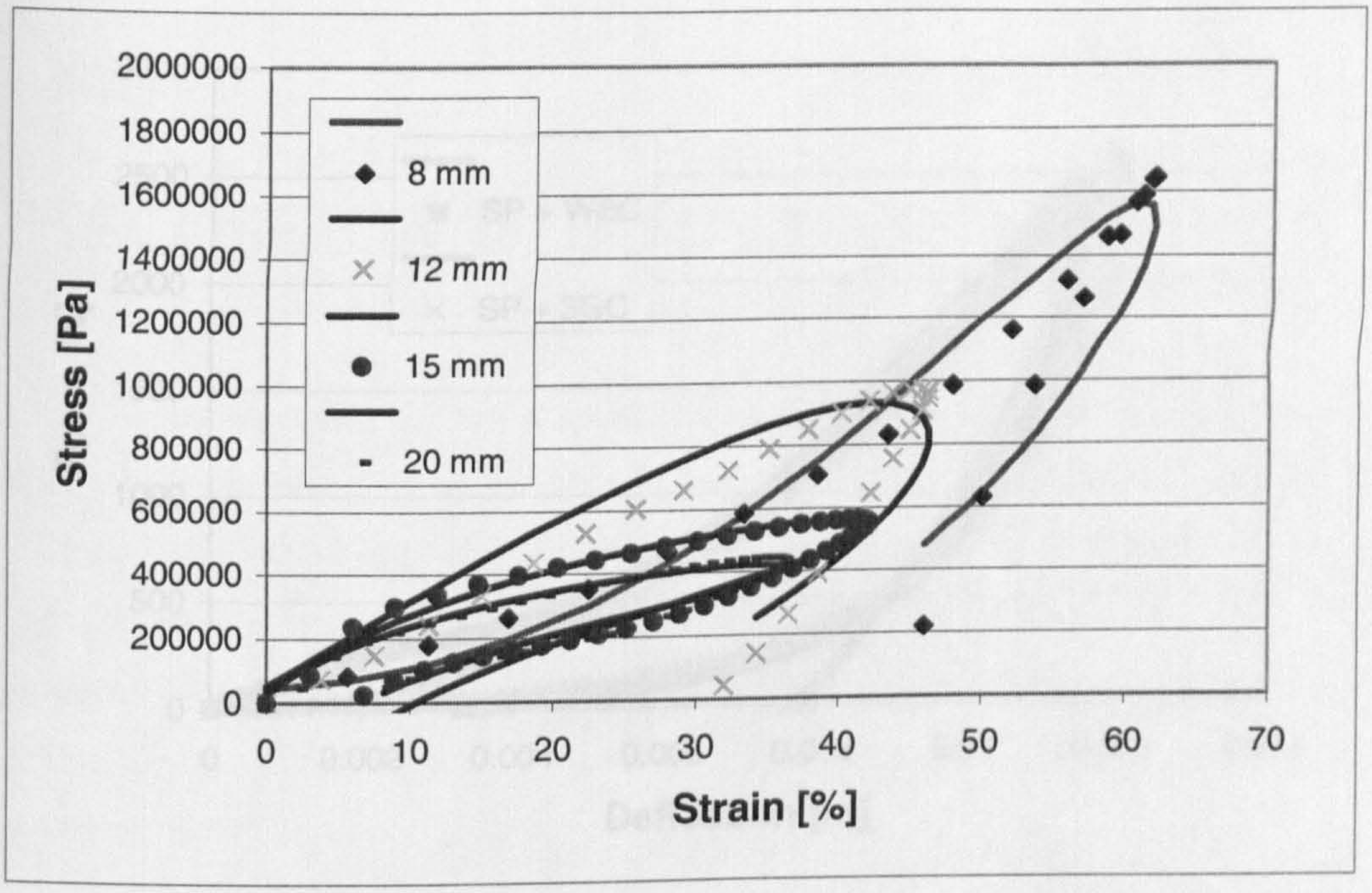


Figure 5.41: Comparison of stress strain model to force plate data for shockpads 8 to 20 mm in thickness for hockey ball impacts

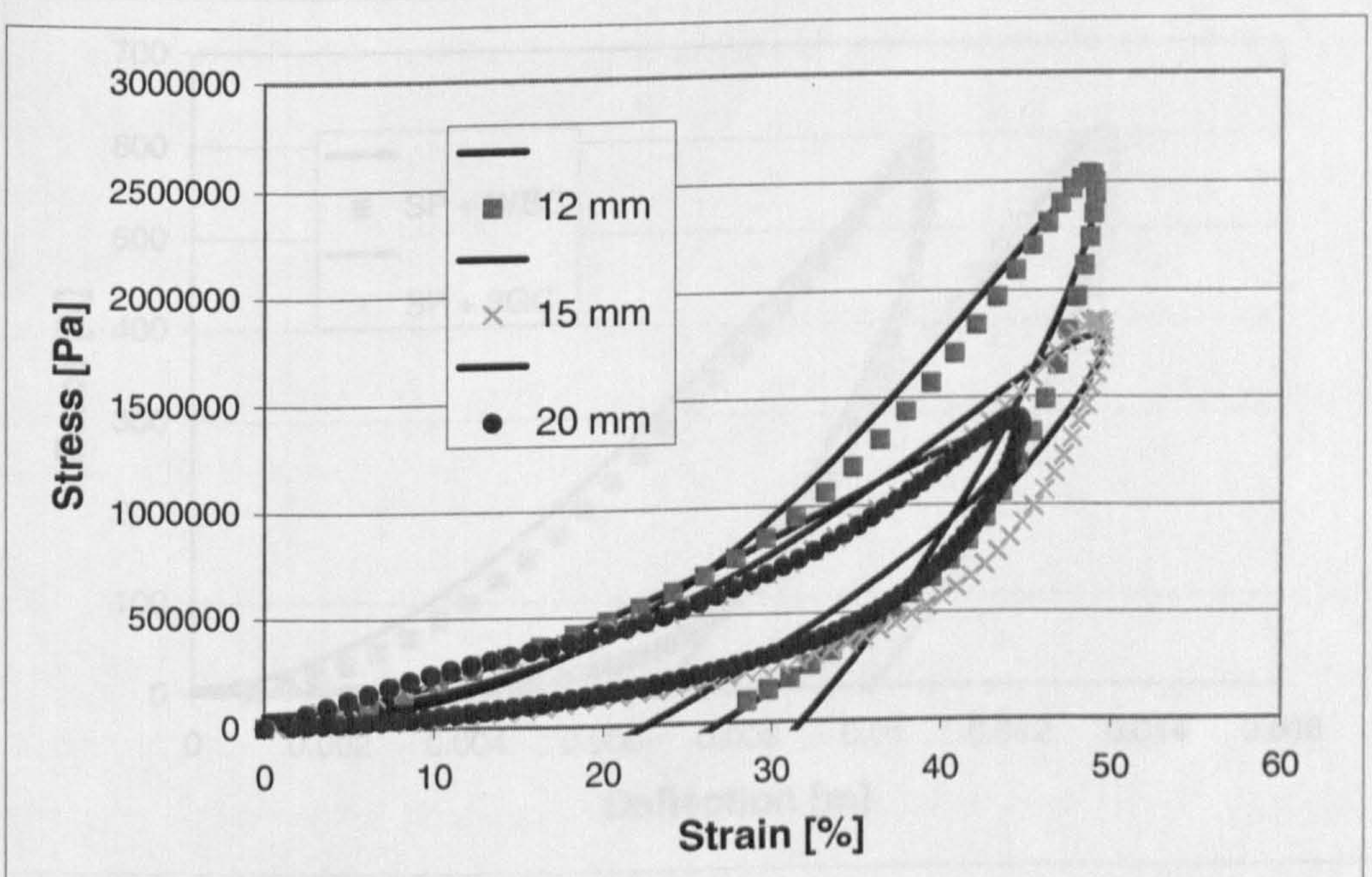


Figure 5.42: Comparison of stress strain model to force plate data for shockpads 12 to 20 mm in thickness for Clegg Hammer impacts

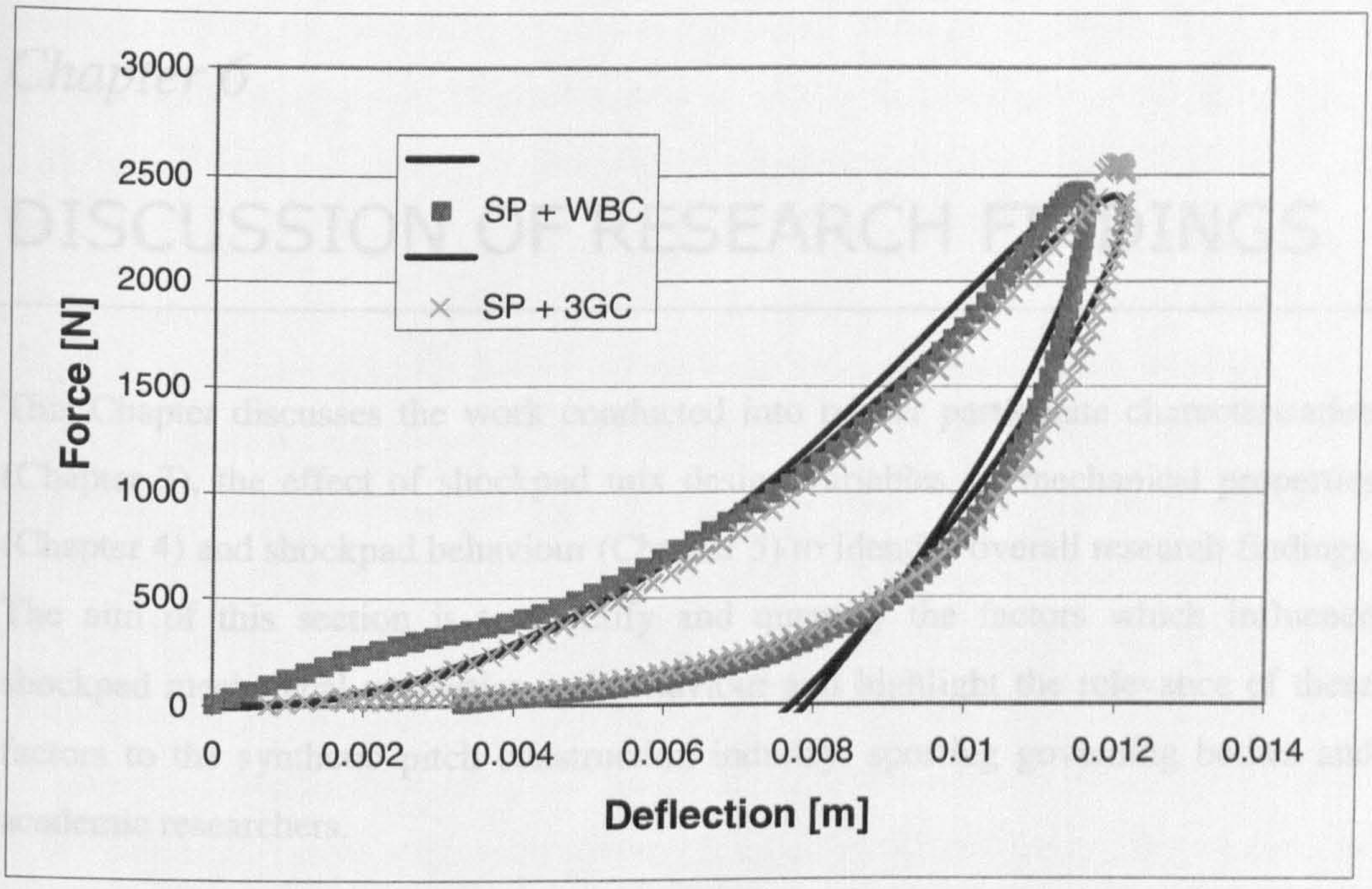


Figure 5.43: Comparison of non-linear damped model and force plate data for benchmark shockpad-water based carpet system and benchmark shockpad-3rd generation carpet system for Clegg Hammer impacts.

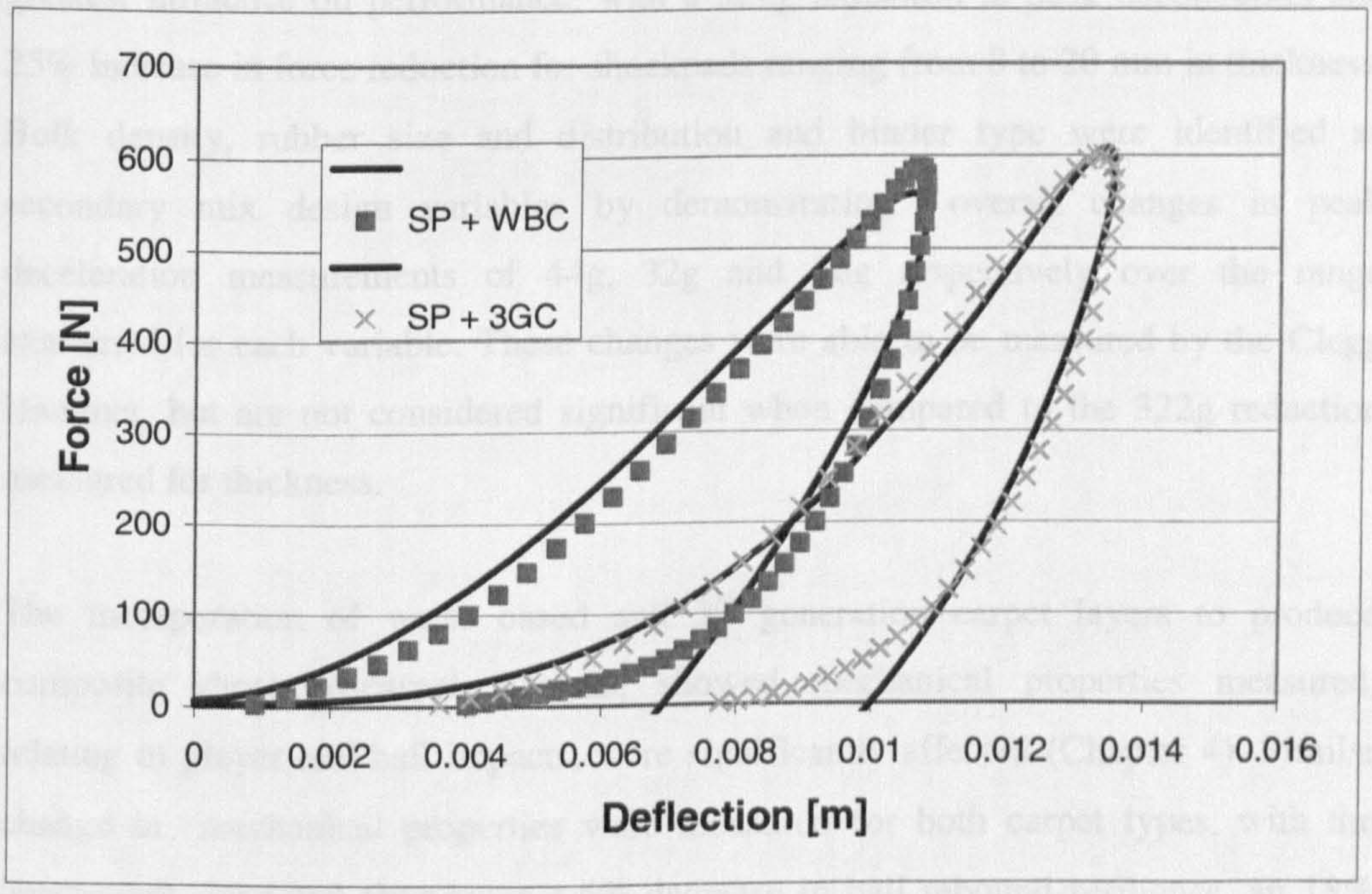


Figure 5.44: Comparison of non-linear damped model and force plate data for benchmark shockpad-water based carpet system and benchmark shockpad-3rd generation carpet system for hockey ball impacts

Chapter 6

DISCUSSION OF RESEARCH FINDINGS

This Chapter discusses the work conducted into rubber particulate characterisation (Chapter 3), the effect of shockpad mix design variables on mechanical properties (Chapter 4) and shockpad behaviour (Chapter 5) to identify overall research findings. The aim of this section is to identify and quantify the factors which influence shockpad mechanical properties and behaviour and highlight the relevance of these factors to the synthetic pitch construction industry, sporting governing bodies and academic researchers.

The investigation into the effect of shockpad mix design on mechanical properties (Chapter 4) showed shockpad thickness to be the mix design variable with the greatest influence on performance, with a 322g reduction in peak deceleration and 25% increase in force reduction for shockpads ranging from 8 to 20 mm in thickness. Bulk density, rubber size and distribution and binder type were identified as secondary mix design variables by demonstrating overall changes in peak deceleration measurements of 44g, 32g and 16g respectively over the range examined for each variable. These changes were able to be measured by the Clegg Hammer, but are not considered significant when compared to the 322g reduction measured for thickness.

The incorporation of water based and 3rd generation carpet layers to produce composite shockpad-carpet systems, showed mechanical properties measured, relating to player and ball impacts, were significantly affected (Chapter 4). Similar change in mechanical properties were measured for both carpet types, with the benchmark shockpad showing a 4.5% decrease in ball rebound resilience, an 18% increase in force reduction and a 140g decrease in peak deceleration with the addition of a carpet layer above the shockpad. Shockpad thickness was the only mix design variable to show a significant effect on the shockpad-carpet system's mechanical properties, whereby a 45g decrease in peak deceleration was measured for both carpets by increasing thickness from 8 to 20 mm. In general, it was found that the addition of a carpet layer produced much larger effect on player and ball interactions than the shockpad mix design changes for when testing the shockpad alone.

The results of mechanical property testing provided an identification of primary and secondary mix design variables and demonstrated the effect of the addition of a carpet layer above. These findings warranted further investigation to provide a 'global' description of the mechanisms of shockpad deformation during an impact (Chapter 5). The significant effects of shockpad thickness and carpet layers on mechanical properties, both identified in Chapter 4, were of particular importance in providing a comprehensive understanding of shockpad behaviour and its contribution to the shockpad-carpet system behaviour. Further, additional factors that influenced shockpad behaviour, such as the impactor itself, were also required to be included in this examination.

The force-deflection behaviour of shockpads was calculated from force plate measurements and has shown a strong non-linear relationship during both loading and unloading, displaying significant hysteresis (energy loss). The results enabled a mechanical model to be developed to describe this behaviour, which was combined with mechanical behaviour data of the rubber particulate (Chapter 3) to provide an insight into the contribution of the rubber particulate and the void space in the shockpad to its behaviour. Initially, when testing the rubber particles in a rigid mould, the behaviour of the rubber particulate was clearly non-linear when a large proportion of voids were present (i.e. loose state) in the mould. However, through the reduction of air voids with increasing cycles of compression, the force deflection behaviour was observed to become increasingly linear. These findings assisted in the classification of the three distinct phases of the loading behaviour of shockpads based on force plate data. The three phases of shockpad behaviour were termed air void compression, transition and rubber compression. The following mechanisms were used to describe and explain the shockpad behaviour at each phase during loading and are represented graphically in Figure 5.18.

Phase 1: Air Void Compression

Deformation of the shockpad is facilitated by compression of the air void structure contained within the shockpad. This phase dictates initial stiffness and deflection to reach transition phase and typically occurs over the 0 to 20% strain range.

Phase 2: Transition

Characterised by the transition from low to a higher stiffness response where there is some further compression of smaller air voids and initial stages of rubber particulate compression. The number of rough edged small particles in contact increases but there is relatively small resistance to deformation at these intermediate strain ranges (e.g. 20 to 60%)

Phase 3: Rubber Compression

Deformation in this phase is characterised by a high stiffness response from significant compression of the rubber particulate. This phase dictates final stiffness, peak impact forces and peak deflection and typically occurs at strains greater than 60%.

The shockpad mix design, impactor adjacent carpet and foundation layers and shockpad degradation influenced the shockpad response and the manifestation of Phases 1 to 3. These factors influencing shockpad behaviour are summarised in Figure 6.1 and are discussed in further detail in the following sections.

Mix design variables

Thickness was shown to be a key mix design variable, by significantly altering the mechanical properties and response of the shockpads, and was investigated further to determine its overall effect on shockpad behaviour. The Clegg Hammer peak impact force was able to be reduced from 4900 N to 2700 N by varying shockpad thickness from 12 to 20 mm during force plate testing. The change in average stiffness between Phase 1 and 3 ranged from 449 to 238 % for the 12 to 20 mm range in thickness, demonstrating increasingly non-linear behaviour with decreasing shockpad thickness.

Shockpad thickness was not shown to affect the magnitude of deflection required to reach Phase 2. Secondary mix variables of bulk density, rubber size and distribution and binder type were observed to produce changes in the mechanical properties of shockpads (Chapter 4) but the effects were not as pronounced as shockpad thickness. Investigating the combined effect of these variables on shockpad behaviour was not considered within the scope of this thesis; however their effect on the three phases of shockpad behaviour can be inferred.

Bulk density variations increase or decrease the initial air void content of shockpads. The compression of air voids is the main mechanism of deformation in Phase 1 and therefore increasing the air void content by lowering bulk density is expected to increase the deformation of the shockpad before reaching Phase 2, which may subsequently lead to reduced peak impact force and Phase 3 stiffness. Rubber particle size and size distribution influences the number of contact points between rubber particles and the surface area of the rubber. Decreasing the average rubber particle size within a distribution increases rubber surface area, decreasing binder coating thickness, but also increases the number of contact points between rubber particles. Lower binder coating thicknesses are expected to allow more displacement of the rubber particles in Phase 1, but also presents a compromise with increased rubber contact points restricting rubber particle movement. Similar behaviour is expected for binder type, where changes in binder mechanical properties will influence the ability of rubber particle to temporarily deform to fill air voids in Phase 1 and also determine the ease of rubber deformation in Phases 2 and 3.

Overall, mix design variables were shown to affect both shockpad mechanical properties and behaviour. Thickness was shown to be the key variable, with measurable changes for both mechanical properties and behaviour. Secondary mix design variables of bulk density, rubber size and distribution and binder type were also shown to produce variations in mechanical properties. All mix design variables, particularly thickness and binder content, were shown to affect shockpad durability indirectly, assessed through shockpad tensile strength). In response to these findings, recommendations were made to the shockpad construction industry and sporting governing bodies that all shockpad mix design variables should be well specified, and measures put in place to control the possible sources of variation, and that verification testing should be conducted post-construction to ensure the mix design specifications are met in the as-constructed shockpad. This improved specification and testing of mix design variables for shockpads is expected to produce improved consistency for construction quality and hence uniformity of performance for similar designs.

Effect of adjacent layers

Foundation and carpet layers, placed directly adjacent to the shockpad layer, were shown to influence the shockpad mechanical properties and response behaviour, and demonstrates the 'composite' nature of the whole pitch system. Placing a carpet layer above the shockpad to form a composite shockpad-carpet system reduced the force (and impact energy) transferred to the shockpad. Overall, the effect of including a carpet layer reduced peak impact forces, reduced Phase 3 stiffness and increased peak deflection. For both ball and simulated player impacts, the addition of a carpet layer to the benchmark produced a 50% reduction in the peak impact force and for player interactions Phase 3 average stiffness reduced from 1600 kN/m for the shockpad to 267 kN/m and 400 kN/m for the water based and 3rd generation carpet systems respectively. The stiffer response of the 3rd generation carpet system, compared to the water based carpet, was not expected due to the thick rubber in-fill contained within the carpet pile. However, this response may be explained by the spray of rubber particulate that was produced during impacts that reduced the in-fill available for shock absorption.

The foundation layer was also shown to influence the measured properties and behaviour for relatively thin (8-12 mm) shockpads. Thinner shockpads showed reduced ball rebound resilience, increased peak deceleration and decreased force reduction for mechanical property measurements conducted in Chapter 4. Further measurements of shockpad behaviour demonstrated the effect of the foundation layer on thin shockpads, which was most evident in the stress-strain relationship. Thicker shockpads (15 and 20 mm) followed a similar load and unload stress-strain behaviour, whereas the thinner 8 and 12 mm shockpads showed increased non-linearity and higher modulus.

Overall, the findings of both the carpet and foundation layers adjacent to the shockpad can significantly influence mechanical property and behaviour measurements. The addition of the carpet layer produced significant changes in mechanical properties and behaviour, however, surprisingly both types of carpet layer produced similar results. The behaviour of the foundation layer only played a significant role in property and behaviour measurements for thin shockpads. These findings have implications for synthetic pitches incorporating thin shockpads or pitches which omit using a shockpad in favour of using 'dynamic' foundations which has a lower stiffness than engineered tarmacadam foundations. The overall effects of adjacent layers highlights how different layers of the pitch can influence its overall mechanical properties and behaviour.

Effect of degradation

The effect of mechanical degradation of shockpads on mechanical properties was studied through cyclic fatigue testing (Chapter 4). The results of cyclic fatigue testing, which was intended to measure shockpad durability, also demonstrated how the mechanical properties of a shockpad will change over time due to mechanical degradation. During the preliminary stages of test method development, the effects of binder content and shockpad thickness on mechanical properties were observed over a degradation period estimated as equivalent to 8 years of in-service use. Ball rebound resilience remained unaffected with degradation. However, Clegg Hammer peak deceleration values increased for both mix design variables. The increase in peak deceleration values was attributed to a permanent reduction in shockpad thickness produced by the mechanical degradation, which was most evident in the 20 mm shockpad and resulted in a 1.5 mm reduction in thickness. This reduction in thickness results in further mix design changes by increasing bulk density, in this case an increase in bulk density from 550 to 595 kg/m^3. Measurable differences in shockpad mechanical properties were recorded by increasing bulk density from 550 to 600 kg/m^3 in the testing programme which therefore may also contribute to mechanical property changes in addition to the thickness reduction

The effect of carpet degradation was not examined in this thesis as it was not considered within its scope; however its likely effect can be inferred. The introduction of the carpet layer produced significant changes to mechanical property and behaviour measurements by reducing the force (and energy) transferred to the shockpad layer. Energy transferred to the carpet during the impact is reduced by the deformation of the carpet pile, and the rubber and sand in-fill (for the 3rd generation carpet) and the integral shockpad (water based carpet). However, as carpet pile begins to degrade and the in-fill compacts less of the impact force and energy (from players and balls) is used in deforming the carpet layer and greater energy is then transferred to the shockpad layer. With increasing degradation of the carpet layer, the mechanical properties and response behaviour of the shockpad-carpet system is expected to move more toward pure shockpad behaviour, and this would represent significant changes in ball and player interactions of the pitch. It therefore thought that is for safety reasons a higher impact absorption response is required at the start of the pitch life to ensure a minimum level is maintained during the in-service life.

Mechanical degradation of the shockpad and carpet layers for in-service synthetic pitches is expected to produce a combined effect of increasing peak impact forces and Phase 3 stiffness over time. The additional effect of environmental degradation, which has not yet been included in cyclic fatigue testing, is expected to further accelerate the whole pitch degradation. These findings highlight the need for shockpad and carpet manufacturers to understand how the mechanical properties of their products will change over time and to conduct sufficient product development to ensure performance requirements, stipulated by sporting governing bodies, are met throughout the entire service life.

Effect of impactor

Shockpad mechanical properties were measured using three different impactor types, a hockey ball, a 2.25 kg Clegg Hammer and a Berlin Artificial Athlete (Chapter 4). The Clegg Hammer and Berlin Artificial Athlete transferred similar impact energy of 9.9 J to the shockpad (or carpet) to simulate player impacts, while the hockey ball transferred an impact energy of 2.3 J, which is clearly considerably less. The Clegg Hammer demonstrated the most sensitivity to measuring variations in mix design, which was attributed to its high impact energy and high rate of loading.

A clearer understanding of the effect of the impactor was gained from repeating hockey ball and Clegg Hammer impacts on shockpads and shockpad-carpet systems and comparing the behaviour produced by each impactor type. The two different impactors differed in terms of impact energy, impact velocity, mass, shape and stiffness. Altering each impactor variable through a range of values to determine trends in behaviour was not within the scope of this thesis; but the effect of using different impactor types could still be compared.

The energy input by the Clegg Hammer was slightly more than 4 times that of the hockey ball; however, both impactors produced an energy return of 38% for the benchmark shockpad, suggesting energy return is dependent on the properties of the shockpad, not the input energy of the impactor. Both impactors also produced a similar maximum deflection, and since input energy is given by the area below the force-deflection curve, the additional potential energy of the Clegg Hammer resulted in an impact force of 5000 N compared with 1300 N for the ball impact for force plate measurements. The different rate of loading applied by the two different impactors was observed in the deflection required to reach Phase 2. The 1.7 mm deflection required by the Clegg Hammer impact compared with the 2.2 mm deflection of the ball impact demonstrated shockpad behaviour was influenced by the rate of loading applied by the impactor.

The two impactors had a distinctly different shape. The flat-faced Clegg Hammer provided a constant contact area with the shockpad, while the contact area between the shockpad and spherical hockey ball increased with deflection. The effect of varying impactor shape was not isolated from other impactor variables and therefore was not directly measured; however, the spherical shape of the ball was anticipated to produce a more complex range of phases of behaviour laterally and across the cross-sectional thickness than the Clegg Hammer.

Overall, the impactor represents the ball or a player and its interaction with an in-service shockpad or whole pitch system. The effect of using different impactors has demonstrated an effect on shockpad mechanical properties and response behaviour. Therefore, it is anticipated players of varying mass, performing various movements, will produce varying shockpad behaviour such as peak impact forces, Phase 3 stiffness and as a result of these the peak deflection. These aspects of shockpad and whole pitch behaviour potentially influence player injury and fatigue, and therefore pitch systems must be designed to accommodate a range of different players.

Combining the findings from each section of work contained in this thesis has shown the shockpad mechanical properties and behaviour is influenced by shockpad mix design, mechanical degradation, the adjacent carpet and foundation layers and the type of impactor used. In light of these findings, the recommendations made to the shockpad construction industry and sporting governing bodies are that: shockpad mix design should be well specified and verified post–construction, that whole pitches should be designed with consideration of the effects of shockpad and carpet degradation during its life, and the required response should accommodate the likely wide range of players (i.e. mass and movements) using the synthetic pitch without significant risk of injury or fatigue to the users.

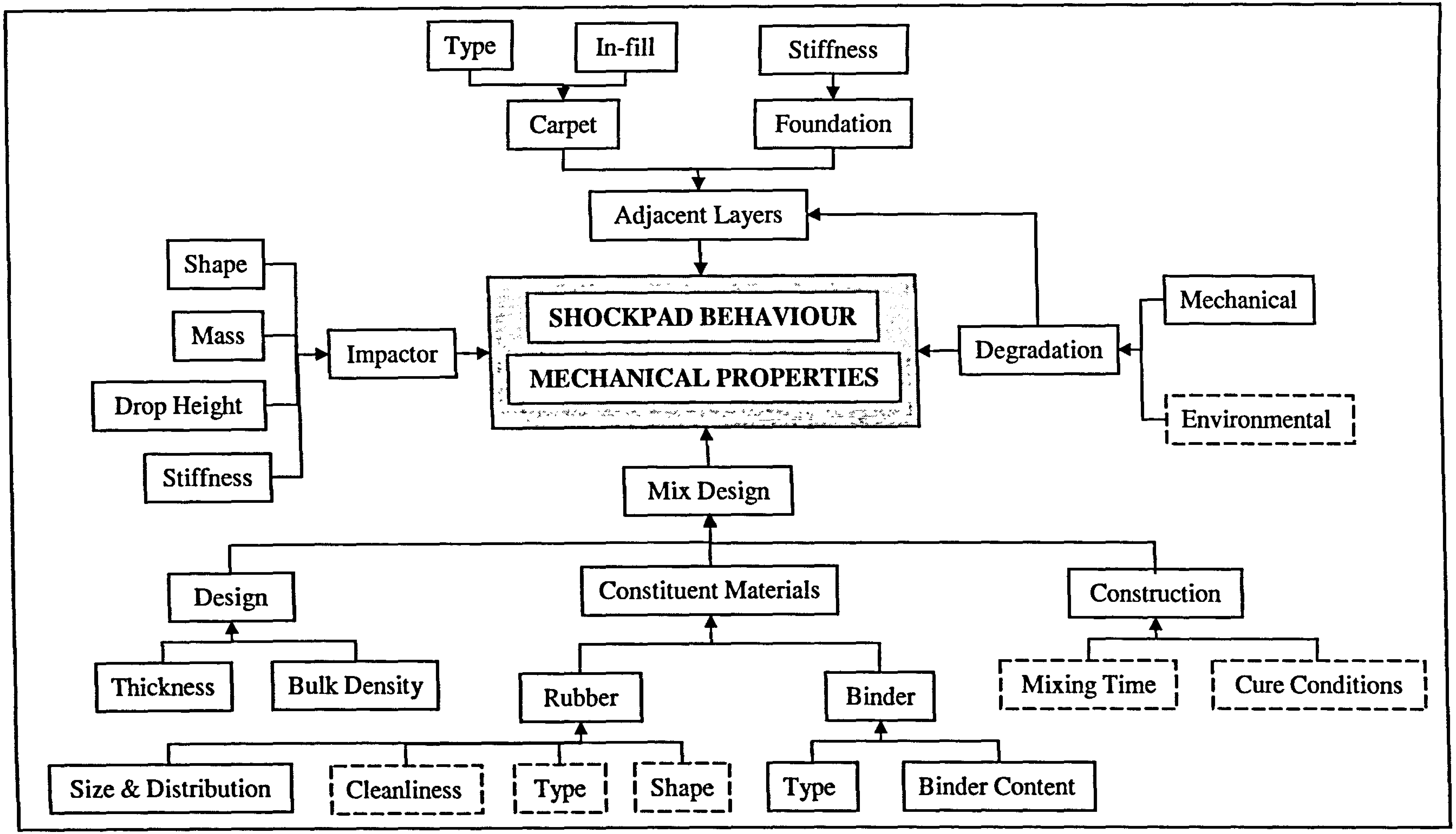


Figure 6.1: Diagram demonstrating factors which affect shockpad behaviour and mechanical properties

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7.1 Introduction

This chapter outlines the conclusions and recommendations for the thesis. Key findings from the thesis are identified in the conclusions section and a section outlining the contributions of this research project towards furthering the understanding of shockpad layers in academia and the sports surfacing industry is also provided. This chapter is concluded with two sets of recommendations. The first set of recommendations is directed towards academic research and identifies further work required to address key research issues regarding shockpads which was identified by the literature review and throughout the course of this research project that can follow on from the work contained in this thesis. The second set of recommendations are directed towards the sports surfacing construction industry and sporting governing bodies and are based on research findings and test methods developed throughout this research to further develop improved specification, testing and consistency for shockpad design and construction. The chapter is concluded with a current list of publications produced from the findings of this thesis.

7.2 Conclusions

The literature review concluded there was a lack of detailed scientific investigation into shockpad layers. It identified mix design, mechanical properties, shockpad behaviour, quality control test methods and modelling as areas of research that could provide a clearer understanding of this layer to the sports surface construction industry and sporting governing bodies. In particular, it was concluded that inadequate quality control test methods were currently available, for shockpads and recycled rubber particulate, to manufacturers to ensure minimum variability within each pitch construction and between different pitches with the same shockpad specification. The current industry test methods and general knowledge of the effects of the many mix design variables were based on relatively low quality 'rule-of-thumb' measurements, anecdotal evidence of performance and manufacturer experience, and were clearly not developed through any programme of rigorous scientific investigation.

The key findings from the programme of research aimed at addressing the knowledge gaps identified in the literature review are outlined below.

Recycled rubber particulate was shown to an inhomogeneous mix of natural and synthetic rubber blends. For the batch of recycled rubber tested, produced wholly from post-consumer truck tyres, the differing rubbers used for each tyre section were concluded to not produce measurable variation in the mechanical properties and behaviour of the shockpads it was used to produce.

However, different tyre or rubber feedstock and processing method (ambient or cryogenic) used to produce the particulate may result in varying composition, physical properties, shape and size distribution. Further test methods and specifications are therefore recommended to be stipulated within the sports surface construction industry for recycled rubber particulate due to the incorporation of other rubber materials such as door seals and trims by some producers. Preliminary measurements taken using the vertical compression test showed potential for its implementation as an indicator of the final mechanical properties of a shockpad based on the mechanical properties of the rubber particulate.

Shockpad thickness was identified as a primary mix design variable and bulk density, rubber size and distribution and binder type were identified as secondary mix design variables. Key findings for mechanical testing conducted directly on the shockpad indicated ball rebound was only influenced by shockpad thickness of less than 12 mm. Player interactions were influenced by shockpad thickness, bulk density, binder type and rubber particle size and size distribution. Shockpad durability measured indirectly by the tensile test, was affected by all variables, in particular binder content. Preliminary cyclic fatigue measurements showed shockpad thickness and binder content to influence shockpad durability. The addition of new carpet layers reduced the effect of mix design variables for player and ball interactions. However, it is concluded both primary and secondary variables and binder content require further specification and verification tests to be implemented to ensure acceptable whole pitch mechanical properties are exhibited over the service life of the pitch.

This absence of non-destructive, rapid and portable tests to determine the variability of mechanical properties across a pitch construction led to the adaptation of the 'Clegg Hammer' impact test for this purpose. The test was sensitive to variations in thickness, bulk density, binder type and rubber particle size and distribution. It is recommended this test be conducted on cured shockpads prior to carpet installation to identify mix design variations across the pitch and highlight any areas in need of relaying.

It was found throughout the course of this investigation that the current tensile test did not represent the mechanisms of mechanical degradation that influence the durability of shockpads and that as all mix design variables affect the tensile strength the test is not an accurate indicator of binder content. The tensile test is therefore not suitable for its current purpose, and a cyclic fatigue-type test, recommended as more suitable for the purpose of measuring shockpad durability.

Shockpads exhibit non-linear and hysteretic behaviour when subjected to vertical dynamic impacts, such as those from players and balls. Three distinct phases of behaviour were common to all shockpads during the loading phase of both Clegg Hammer and hockey ball impacts, and were termed void compression, transition and rubber compression.

The different mass, shape and drop heights of the two impactors produced force-deflection behaviour that varied in of peak impact force, peak deflection and final shockpad stiffness. Increasing shockpad thickness reduced peak impact forces and final stiffness for Clegg Hammer impacts, which highlighted how shockpad design plays an important role for injury prevention. The addition of a carpet layer also reduced peak impact forces, final stiffness and energy return.

The non linear damped mechanical model, represented by a parallel non-linear spring and linear damper, provided a good description the loading and unloading behaviour of shockpads. The composite shockpad-carpet system was also able to be described by the non-linear damped model.

By combining each section of work, it was concluded shockpad mechanical properties and behaviour are influenced by mix design, mechanical degradation, adjacent carpet and foundation layers and the type of impactor used. Overall, recommendations were made for further specification and post-construction verification tests to be introduced for the shockpad layer, whole pitches be designed with consideration of the effects of shockpad and carpet degradation and the behavioural response should accommodate a range of players using the pitch without significant risk of injury or fatigue.

7.3 Contribution to Knowledge

The review of published literature identified many key knowledge gaps regarding shockpads. Research objectives were developed to address these key knowledge gaps at a level that could be implemented by both the sports surface construction industry and suppliers and also within academia. The conclusions of this research project satisfied the initial objectives by providing a broad level of understanding regarding constituent materials, shockpad mix design and its effect on mechanical properties, shockpad behaviour and the development of a suitable mechanical model to describe this behaviour.

A lack of test methods to control the quality of cast in-situ shockpads was identified in the review of literature. Three tests have been developed to provide further quality assurance and consistency of cast in-situ shockpads produced. Firstly, the vertical compression test was developed to determine mechanical properties of recycled rubber particulate and provide a method to compare different sources of the constituent material of shockpads. Secondly, the rapid, non-destructive and portable Clegg Hammer test was shown to detect changes in shockpad thickness, bulk density, binder type and rubber size and size distribution in-situ, allowing areas in the field varying in mix design to be identified and replaced prior to carpet installation.

A third test, cyclic fatigue, was developed as an alternative test to the tensile test for measurement of shockpad durability. The cyclic fatigue test is considered more accurate at simulating mechanical degradation mechanisms for in service shockpads than the traditional tensile test but is still in its preliminary stages of development.

Particle size distribution was the only parameter specified by the industry for the quality control of recycled rubber particulate supplied for shockpad construction. The extent of variation in properties and composition within a typical batch, and the effect this may have on the shockpads, was not well published in literature or widely known by rubber particulate producers. Characterisation of a typical source of recycled rubber particulate showed small property and compositional variations within a batch that were not capable of adversely affecting shockpad properties. The characterisation tests also provided a set of mechanical and properties and average composition by which other sources could be compared.

Research into the effects of mix design on the mechanical properties of cast in-situ shockpads has created a new knowledge base for constructors of shockpads by identifying key mix design variables and providing a better understanding of how these variables may affect whole pitch performance both initially and as the carpet wears. This testing programme also developed a benchmark shockpad design for testing constituent materials and carpet for product certification purposes. A repeatable laboratory construction method was also developed to produce shockpads for these certification purposes and for sports pitch research.

In addition, measurements of shockpad behaviour were conducted under rates of loading associated with ball and player impacts. The effects of thickness, the key mix design variable, and water based and 3rd generation carpet layers on shockpad behaviour assisted in the development of a mechanical model to describe shockpad behaviour. This model is useful for both development of shockpads to exhibit specific behaviour and also for sports pitch and biomechanics research.

7.4 Recommendations

This section contains two sets of recommendations. The first set of recommendations is directed towards the academic research community and identifies additional work to further this investigation of shockpads for synthetic sports surfaces. The second set of recommendations is directed towards the sports surfacing industry, sporting governing bodies and other interested parties such as sports shoe manufacturers. These recommendations are based on the findings of this research project, and are aimed at improving the current understanding of shockpad design, specification and testing. The two sets of recommendations are detailed in the following sections.

7.4.1 Further Work

The objectives of this thesis were to examine the effects of mix design on the mechanical properties of cast in-situ shockpads, observe the impact behaviour of shockpads and the production of a basic mechanical model to describe shockpad behaviour. This section recommends areas of further work identified in the literature review, or throughout the course of the research project, that could assist in providing a more complete understanding of shockpad layers.

A number of test methods were developed with the intention of increasing the quality control measures currently in place for shockpads produced on site. It is recommended that a binder content test is developed for cured shockpads sampled from the pitch in favour of the current tensile test. Tensile test results where shown to be affected by all mix design variables and therefore does not measure the binder content alone.

The creation of a database of site-laid shockpad mix design specifications and mechanical properties would enable realistic standards to be developed to assist in identifying shockpads that fall outside acceptable quality and performance limits and provide a benchmark for new shockpad developments. This database could be compiled from sourcing further shockpads, intended for a variety of sports and from various pitch constructors.

The investigation into the effects of mix design on the mechanical properties of shockpads was limited to the effect of altering each variable individually while all others remained constant. Extending this investigation to determine the net effect of altering mix design variables simultaneously would show the actual range of mechanical property variations achievable through mix design. An example where contrasting mechanical properties would be anticipated is between large particle sizes combined with small binder contents and small particle sizes combined with large binder contents. In addition, the effect of further variables such as cure temperature and humidity, mixing time, rubber shape and rubber type, which were controlled during this investigation, would provide a more complete understanding of the extent these variables influence the mechanical properties of shockpads.

The effect of mix design on the safety aspects of players were not able to be examined in this investigation. Safety was identified as a functional requirement of shockpads and conducting safety testing with suitable equipment would add to the data on the other functional requirements of ball and player interactions. In addition, ball rebound characteristics of shockpads with varying mix design was examined only with a hockey ball to reduce variables and therefore did not measure the rebound height of football or rugby ball on the 3rd generation pitch. The significant force reduction produced by the long pile and relatively deep in-fill of the 3rd generation carpet was hypothesised to not transfer sufficient force to the shockpad to observe any significant effect from the alteration mix design variables; this could be confirmed through investigation.

The impact behaviour of shockpads was focused on the effect of thickness as it was identified as the key mix design variable in mechanical property tests. Reducing the bulk density of shockpads was hypothesised to delay the onset of the transition phase of behaviour and extending the study to determine the effect of bulk density would confirm this. Other variables such as rubber particle size distribution may also show an effect on shockpad behaviour due to the observed effect on mechanical properties. Further to this, development of the shockpad mechanical model into a composite model which describes the carpet, shockpad and foundation layers as separate elements could be used to describe whole pitch behaviour and the effect of using different shockpads in different systems. The coefficients determined for the mechanical model and constituent material data could be used to construct a more precise model of shockpad behaviour used more advanced modelling numerical modelling such as Finite Element Analysis (FEA).

7.4.2 Industry

This section provides recommendations to the sports surfacing industry based on the research findings and test methods identified within this thesis to improve both the quality and consistency of shockpads constructed on site. The recommendations made throughout this section relate to the lab-based construction and testing of small-scale shockpads due the high accuracy of mix design specifications required. Larger scale, site-based construction and testing were outside the scope of this work. The research methods and findings in this investigation focused on cast in-situ shockpads, however, these recommendations are also applicable to prefabricated shockpads and in general any bound rubber crumb installations for other applications, such as for playground and walkway surfaces for example.

Recommendations for controlled mix design and quality control aspects of shockpad construction are identified in separate sections below. Mix design recommendations are a result of the findings in Chapter 4, which identified key factors in the design of cast on-situ shockpads that affect their mechanical properties. The recommendations for quality control include the possible implementation of further test methods for assessing constructed shockpads and/or the recycled rubber particulate used to construct them. Aspects of shockpad behaviour examined in Chapter 5 were more applicable to furthering academic research and therefore do not form any recommendations to industry, though the simple behavioural model helps explain why some of the physical variables are important.

Mix Design

The effect on the mechanical properties of mix design variables, such as thickness, binder content, rubber size and size distribution and binder type were investigated in detail in Chapter 4. Key findings for testing conducted directly on the shockpad indicated ball rebound was only influenced by shockpad thickness of less than 12 mm. Player interactions were influenced by shockpad thickness, bulk density, binder type and rubber particle size and size distribution. Shockpad durability measured indirectly by the tensile test, was affected by all variables, in particular binder content. Preliminary cyclic fatigue measurements showed shockpad thickness and binder content to influence shockpad durability.

When the shockpads were tested in combination with a water based and a 3rd generation carpet, only shockpad thickness affected player interaction characteristics and there was no effect of any variables for ball interactions. However, as the carpet wears and the in-fill compacts it is anticipated that more force will be transferred to the shockpad. Thus, over the life of the surface system, the effect of thickness, bulk density, binder type and particle size and size distribution may begin to influence the ball and player response to a greater extent.

The results of the mix design testing programme show all mix design variables to influence the mechanical properties of shockpads to varying degrees. Shockpad thickness was shown to be the key mix design variable, influencing ball and player interactions with and without the carpet layer. It is therefore recommended that sports pitch manufacturers ensure careful control of shockpad thickness to ensure consistent properties across a pitch. Binder content, bulk density and rubber particle size and distribution and binder type should also be controlled and measured for each pitch construction.

Quality Control

Currently, shockpad quality control is provided by the construction of a shockpad sample which is tested for tensile strength to indicate sufficient binder content and durability. This absence of non-destructive, rapid and portable tests to determine the variability of mechanical properties across a pitch construction led to the adaptation of the 'Clegg Hammer' impact test for this purpose. The test was sensitive to variations in thickness, bulk density, binder type and rubber particle size and distribution. It is recommended this test be conducted on cured shockpads prior to carpet installation to identify mix design variations across the pitch and highlight any areas in need of relaying. The results of Clegg Hammer testing form a base of acceptable Clegg Hammer values for each mix design variable, however the development of a database for the mechanical properties of further pitches will assist in the development of target Clegg Hammer impact values.

An accelerated cyclic fatigue test was developed to as part of this investigation to better simulate the mechanical degradation mechanisms of shockpads to measure the response under many cycles of load. Preliminary cyclic fatigue test results showed potential for the test to be implemented as a more suitable test for mechanical durability. In addition, for the purposes of disputes between constructor and client and as direct verification method, a test method to determine binder content is recommended. One possible method was trialled as part of this investigation, however, preliminary measurements proved to not be of sufficient accuracy.

It is recommended that rubber particulate suppliers should supply details of the particle size distribution as currently required and also include details of the typical physical properties, such as density and hardness, and also composition and mechanical properties. In addition, a number of quality issues such as rubber shape, rubber type and rubber cleanliness (dust, fibre and steel content) were controlled throughout this investigation. As there are no current test methods or specifications to measure and control these variables in industry it is recommended pitch manufacturers are made aware of them and minimise their variation through careful specification or though good knowledge of their suppliers.

7.5 List of Publications

Anderson, L.J., Fleming P.R. and Ansarifar, A. (2004) *Shock Absorbing Layers for Synthetic Sports Pitches,* In: The Engineering of Sport 5, (Eds. M. Hubbard, R. D. Mehta, and J.M Pallis), Vol. 2, pp. 509-516

Anderson, L.J., Fleming P.R. and Ansarifar, A. (2006) *Recent Advances in Understanding the Behaviour of Shockpads for Outdoor Synthetic Sports Pitches,* In: The Engineering of Sport 6, (Eds. E.F. Moritz and S. Haake), Vol 3, pp. 97-102

REFERENCES

Abbott, M. (2003) *Beneath the Surface – Technical Guidance Leaflet No. 1*, Sports and Play Contractors Association, Stoneleigh, UK

Adhikari, B., De, D. and Maiti S. (2000) *Reclamation and Recycling of Waste Rubber*, Progress in Polymer Science (25), pp. 909-948

Adrian M. and Xu D. (1990) *Matching the Playing Field to the Player*, In: Natural and Artificial Playing Fields: Characteristics and Safety Features (Ed. R.C. Schmidt), American Society for Testing and Materials, Philadelphia, USA, pp. 10-19

American Society for the Testing of Materials (1996) ASTM D5603-96, *Standard Classification for Rubber Compounding Materials - Recycled Vulcanizate Particulate Rubber*, Philadelphia, USA

American Society for the Testing of Materials (1996) ASTM D5644-96, *Standard Test Method for Rubber Compounding Materials - Determination of Particle Size Distribution of Vulcanized Particulate Rubber*, Philadelphia, USA

Barbin, W.W. and Rodgers, M.B. (1994) *The Science of Rubber Compounding*, In: Science and Technology of Rubber (Ed. Mark, J.E., Erman, B. and Eirich, F.R.), Academic Press, London UK

Bartlett, R. (1999) *Sports Biomechanics: Reducing Injury and Improving Performance*, E & FN Spon, London, UK

Bennett, G. (2005) – MRPRA – Personal Communications

Blackburn, S., Nicol, A.C. and Walker, C. (2005) *Development of a Biomechanically Validated Turf Test Rig*, Research Poster, University of Strathclyde

Bloxham, J.L. (1962) *Applications of Reclaimed Rubber in Tyre Compounding*, In: Reclaimed Rubber (Ed. A. Nourry), Maclaren & Sons Ltd, London, UK

Breland, (1990) *Performance Standards for Artificial Turf Surfaces*, In: Natural and Artificial Playing Fields: Characteristics and Safety Features (Ed. R.C. Schmidt), American Society for Testing and Materials, Philadelphia, USA, pp. 176-182

British Standard (2002) prBS EN 14243:2002 – *Post Consumer Tyre – Materials and Applications*, London, UK

British Standard (2003) BS EN ISO 604:2003 – *Plastics: Determination of compressive properties*, London, UK

British Standard (1998) BS EN 1177:1998 - *Impact absorbing playground surfacing: Safety requirements and test methods*, London, UK

British Standard (1980) BS 5835-1:1980 - *Recommendations for testing of aggregates. Compactibility test for graded aggregates*, London, UK

British Standard (1996) BS 903-A1:1996 - *Physical Testing of Rubber – Determination of Density*, London, UK

British Standard (1995) BS 903-A26:1995 - *Physical Testing of Rubber – Method for Determination of Hardness*, London, UK

British Standard (1990) BS 7044 – *Artificial Sports Surfaces*, London, UK

Brown, R. (2006) *Physical Testing of Rubber*, Springer, New York, USA

Burford, R.P. and Pittolo M. (1982) *Characterisation and Performance of Powdered Rubber*, Rubber Chemistry and Technology (55), pp. 1233-1249

Carré, M.J., Dodd, D., Senior, T. and Haake, S.J. (2004) *A System for Predicting the Impact Between a Ball and a Sports Surface*, In: The Engineering of Sport 5, (Eds M. Hubbard, R. D. Mehta, and J.M. Pallis) pp. 45-51

Cavanagh, P.R. and Lafortune, M.A. (1980) *Ground Reaction Forces in Distance Running*, Journal of Biomechanics, (13), pp. 397-406

Charles Lawrence PLC (2003) – www.clgplc.co.uk - Accessed 14th September 2003

Comyn, J. (1997) *Adhesion Science*, Royal Society of Chemistry, Cambridge, UK

Conica (2001) *Technical Data Sheets*, Schaffhausen, Germany

Continental Tyres (1999) *Truck Tyre Basics*, Germany

Craig, R.F. (1997) *Soil Mechanics*, 6th Edition, E & FN Spon, London, UK

Crawshaw, G.H. (1989) *Textile Sports Surfaces and Artificial Grass*, Elsevier Science Publishers Ltd, Oxford, UK

Cui, H., Yang, J. and Lui, Z. (1999) *Thermogravimetric Analysis of Two Chinese Used Tyres*, Thermochimica Acta, 333, pp. 173-175

Dixon, S.J., Batt, M.E. and Collop, A.C. (1999) *Artificial Playing Surfaces Research: A Review of Medical Engineering and Biomechanical Aspects*, International Journal of Sports Medicine, 20(4), pp. 209-218

Dixon, S.J., Collop A.C. and Batt, M.E. (2000) *Surface Effects on Ground Reaction Forces and Lower Extremity Kinematics in Running*, Medicine & Science in Sports & Exercise, 32(11), pp. 1919-1926

Edwards, B.H. (1986) *Polyurethane Structural Adhesives*, In: Structural Adhesives: Chemistry and Technology (Ed. S.R. Hartshorn), Plenum Press, New York, USA

Fédération Internationale de Football Association (FIFA) (2005) *FIFA Quality Concept: Handbook of Test Methods and Requirements for Artificial Turf Football Surfaces*, Lyon Switzerland

Fédération Internationale de Hockey (1999) *Handbook of Performance Requirements: Synthetic Hockey Pitches – Outdoor*, Lausanne, Switzerland

Figueroa, P.J., Leite, N.J. and Barros, R.M.L. (2005) *Tracking Soccer Players Aiming Their Kinematic Motion Analysis*, Computer Vision and Image Understanding 101(2), pp. 122-135

Fleming, P.R., Dixon, N., Lambert, J. and Young, C. (2002) *Monitoring the Performance of Hockey Pitches During Construction*, In: The Engineering of Sport 4 (Eds. S. Ujihashi and S.J. Haake), Blackwell Publishing, Oxford, UK, pp. 545-552

Fleming P, Young C, Dixon N, (2004) *Performance Measurements on Synthetic Turf Hockey Pitches*, In: The Engineering of Sport 5, (Eds M. Hubbard, R. D. Mehta, and J.M Pallis), Vol 2, pp. 524-531

Football Association (FA) (2005) *Guideline Performance Standards for Outdoor Artificial Grass Pitches for Community Use*, UK

Football Foundation (2004) *Facilities Data Sheet 6*, UK

Forrest, M.J. (2001) *Rubber Analysis – Polymers, Compounds and Products, RAPRA Review Reports*, 12(7), RAPRA Technology, Shrewsbury, UK

French, T. (1989) *Tyre Technology*, Adam Hilger, Bristol, UK

Gabbett, T.J. (2000) *Physiological and Anthropometric Characteristics of Amateur Rugby Players*, British Journal of Sports Medicine, 34, pp. 303-307

Gierenz G. and Karmann W. (2001) *Adhesives and Adhesive Tapes*, Wiley VCH, Weinheim, Germany

Harman, T. and Bukowski, J.R. (2001) *The History and Future Challenges Of Gyratory Compaction 1939 to 2001*, Dept. of Transport, Virginia, USA

Harrison, M. (1992) *Breaking New Ground*, Leisure Management (Jan), pp 59-61

Hepburn, C. (1982) *Polyurethane Elastomers*, Applied Science Publishers, London, UK

Hull, C. (2005) MRPRA – Personal Communications

Huntsman Polyurethanes (2000) *Rubinate MDI Prepolymers for Superior Rubber Crumb Composites*, Michigan, USA

International Association of Athletics Federations (2003) *IAAF Performance Specifications for Synthetic Surfaced Athletics Tracks (Outdoor)*, Monaco

International Rugby Board (2005) *IRB Performance Specification for Artificial Surfaces for Rugby*, Dublin, Ireland

Johnson, K.L. (1985) *Contact Mechanics*, Cambridge University Press, UK

Jones, B. (2003) – www.brianjones.co.uk – Accessed 14th September 2003

Kim, J.K. (1997) *Experimental and Theoretical Studies on Crumb Rubber/Polyurethane Blend System*, Korea Polymer Journal, 5(4), pp. 241-247

Kinloch, A.J. (1987) *Adhesion and Adhesives*, Chapman Hall, London, UK

Klingensmith, W. and Baranwal K. (1998) *Recycling of Rubber – An Overview*, Rubber World, 218(3), pp. 41-46

Kolitzus, H.J. (1984) *Functional Standards for Playing Surfaces*, In: Sports Shoes and Playing Surfaces (Ed. E.C. Frederick), Human Kinetic Publishers Inc, Illinois, USA, pp. 98-117

Kolitzus, H.J. (2000) *Artificial Athlete Berlin - Comments on Function and Use – International Association for Sports Surface Sciences* - http://www.isss.de

Kovac, F.J. and Rodgers, M.B. (1994) *Tire Engineering*, In: Science and Technology of Rubber (Ed. Mark, J.E., Erman, B. and Eirich, F.R.), Academic Press, London UK

Kumho European Technical Centre (2005) – Personal Communications

Leonard, R.G. (1973) *Fundamentals of Dynamic Properties Measurement of Elastomers: Part 1 – Measurement and Identification Principles*, In: The Measurement of the Dynamic Properties of Elastomers (Ed. B.M. Hillberry), Society of Automotive Engineers Inc. New York, USA.

Manuel, H.J. and Dierkes, W. (1997) *Recycling of Rubber*, RAPRA Review Reports, 9(3), RAPRA Technology Ltd, Shrewsbury, UK

Mark, J.E., Erman, B. and Frederick, R.E. (1994) *Science and Technology of Rubber*, Academic Press, London, UK

McCullagh, P.J.J and Graham, I.D. (1985) *A Preliminary Investigation into the Nature of Shock Absorbency in Synthetic Sports Materials*, Journal of Sports Sciences, (3), pp.103-114

McMahon T. and Greene P. (1979) *The Influence of Track Compliance on Running*, Journal of Biomechanics (12), pp. 893-904

Munro, C.F., Miller, D.I. and Fuglevand, A.J (1987) *Ground Reaction Forces in Running: A Re-examination*, Journal of Biomechanics, 20(2), pp. 147-155

Nagdi, K. (1993) *Rubber as an Engineering Material: Guideline for Users*, Hanser, Munich, Germany

Nigg, B.M., Denoth, J., Kerr, B., Luethi, S., Smith D. and Stacoff, A. (1984) *Load Sport Shoes and Playing Surface*, In: Sports Shoes and Playing Surfaces (Ed. E.C. Frederick), Human Kinetic Publishers, Illinois, USA, pp. 1-23

Nigg, B.M. and Yeadon M.R. (1987) *Biomechanical Aspects of Playing Surfaces*, Journal of Sports Sciences, (5), pp.117-145

Nigg B.M. (1990) *The Validity and Relevance of Tests Used for the Assessment of Sports Surfaces*, Medicine and Science in Sports and Exercise, 22(1), pp. 131-139

Nigg, B.M., Cole, G.K. and Bruggemann, G.P. (1995) *Impact Forces During Heal-Toe Running*, Journal of Applied Biomechanics (11), pp. 407-432

Ozguven, H.N. and Berne, N. (1988) *An Experimental and Analytical Study of Impact Forces During Human Jumping*, Journal of Biomechanics, 21(12), pp. 1061-1066

Pavis, B., Junqua, A. and Lacouture, P. (1983) *Validity of Hertzian Contact Theory in Shocks on Playing Surfaces*, In: Biomechanical Aspects of Sports Shoes and Playing Surfaces (Ed. B.M. Nigg and B.A. Kerr), University of Calgary, Canada, pp. 63-72

Peel, J.D. (2002) *Recycled Rubber Crumb – A Growing Market in Safety Surfaces*, British Plastics and Rubber, (April), pp. 20-21

Peterson, C., Ackerly, P. and Rosemergy, H. (2004) *Unlocking the Potential of GPS Athlete Tracking Technology*, Unknown Publication

Rodriguez, F. (1996) *Principles of Polymer Systems*, Taylor and Francis, London, UK

Rouse, M. (1997) *Production, Identification and Application of Crumb Rubber Modifiers for Asphalt Pavements*, In: Asphalt Science & Technology (Ed. A.M. Usmani), Marcel Dekker Inc, New York, USA

Shorten M.R. and Himmelsbach, J.A. (2002) *Shock Attenuation of Sports Surfaces*, In: The Engineering of Sport 4 (Eds. S. Ujihashi and S.J. Haake), Blackwell Publishing, Oxford, UK, pp. 152-159

Sobral, M., Samagaio, A.J.B., Ferreira, J.M.F. and Labrincha, J.A. (2003) *Mechanical and Acoustical Characteristics of Bound Rubber Granulate*, Journal of Materials Processing Technology, 142(2), pp. 427-433

Song, B., Chen, W. and Cheng, M. (2004) *Novel Model for Uniaxial Strain-Rate-Dependent Stress-Strain Behaviour of Ethylene-Propylene-Diene Monomer Rubber in Compression or Tension*, Journal of Applied Polymer Science, 92, pp. 1553-1558

Spencer, M., Lawrence, S., Rechichi, C., Bishop, D., Dawson, B. and Goodman, C. (2004) *Time-motion analysis of Elite Field Hockey – With Special Reference to Repeated-Sprint Activity*, Journal of Sports Sciences, 22, pp. 843-850

Sport England (2003) *A Guide to Design, Specification & Construction of Multi-Use Games Areas Including Multi-Sport Synthetic Turf Pitches – Pt. 3*, London, UK

Stocker, B. (2003) – Murfitts Industries – Personal Communications

Tipp, G. and Watson, V. (1982) *Polymeric Surfaces for Sport and Recreation*, Applied Science Publishers, London, UK

Tipp G. and Watson V. (1983) *Synthetic Surfaces*, National Turfgrass Council, Bingley, UK

Tipp, G. (1992) *Pitching In*, Leisure Management, (July), pp. 63-65

Tipp, G. (1993) *On the Right Track*, Leisure Management, 13(4), pp 44-46

Thomson, R.D., Birbeck, A.E. and Lucas, T.D. (2001) *Hyperelastic Modelling of Nonlinear Running Surfaces*, Sports Engineering, (4), pp.215-223

United European Football Association (UEFA) (2003) *Artificial Turf Requirements and Recommendations*, Nyon, Switzerland

Valiant, G.A. (1987) *The Relationship Between Normal Pressure and Friction Developed by Shoe Outsole Material On A Court Surface*, Journal of Biomechanics, 20(9), pp. 892

Valiant G.A. (1990) *Traction Characteristics of Outsoles for Use on Artificial Playing Surfaces*, In: Natural and Artificial Playing Fields: Characteristics and Safety Features (Ed. R.C. Schmidt), American Society for Testing and Materials, Philadelphia, USA, pp. 61-68

Wake, W.C. (1982) *Adhesion and the Formulation of Adhesives*, Applied Science Publishers, Essex, UK

Walker, C.A. (1996) *Experimental Mechanics and Artificial Turf*, In: The Engineering of Sport (Ed. S.J. Haake), Balkema, Rotterdam, pp. 239-242

Watson, V. (1986) *Synthetic Surfaces for Sport Outdoors*, Leisure Management, (Feb), pp. 45-49

Watson, V. and Tipp, G. (1987) *Impact Absorbing Surfaces*, National Playing Fields Association, London, UK

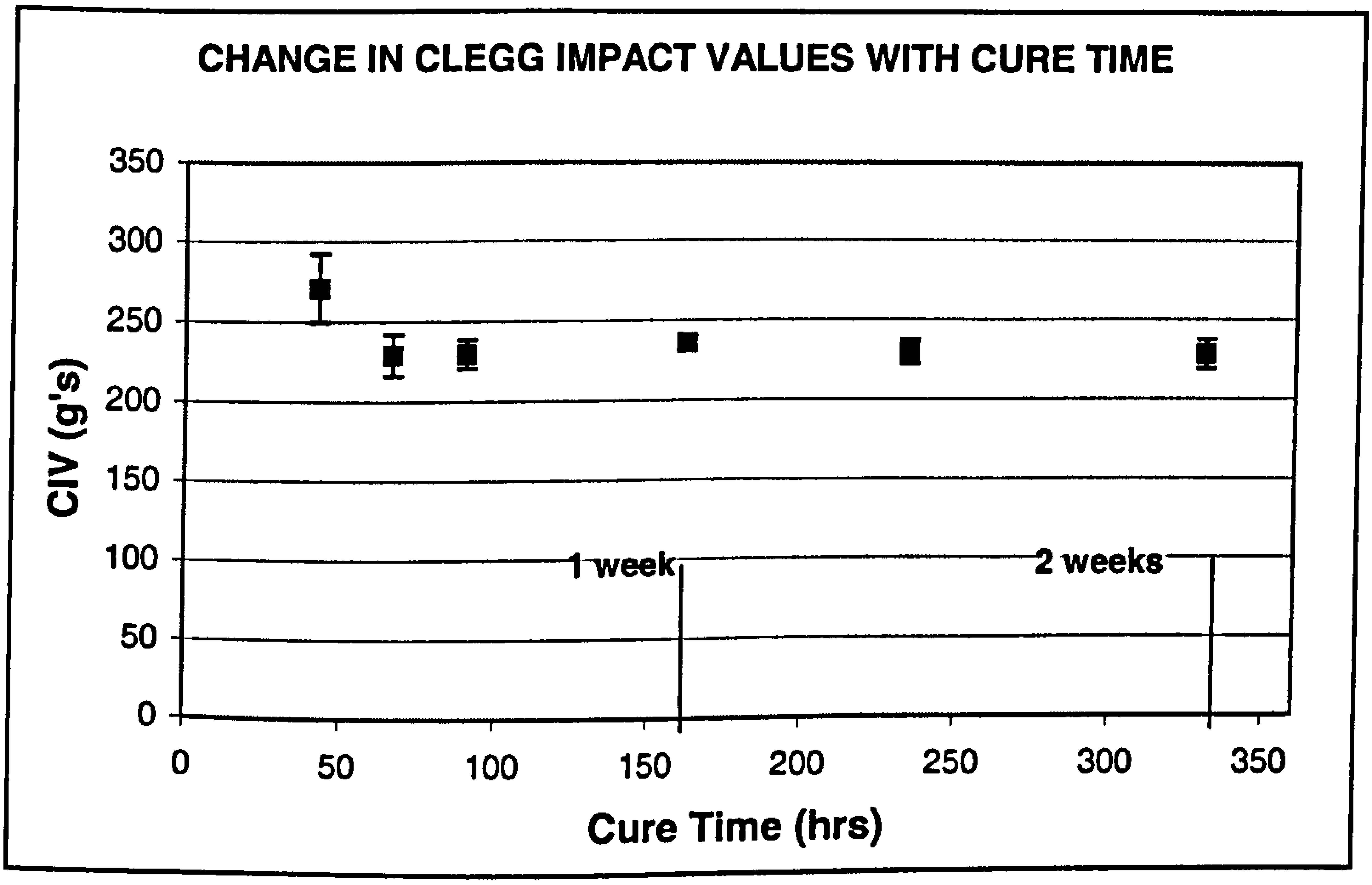
Williams, F. (2006) – Brigham Young University, Utah, USA - Unpublished data

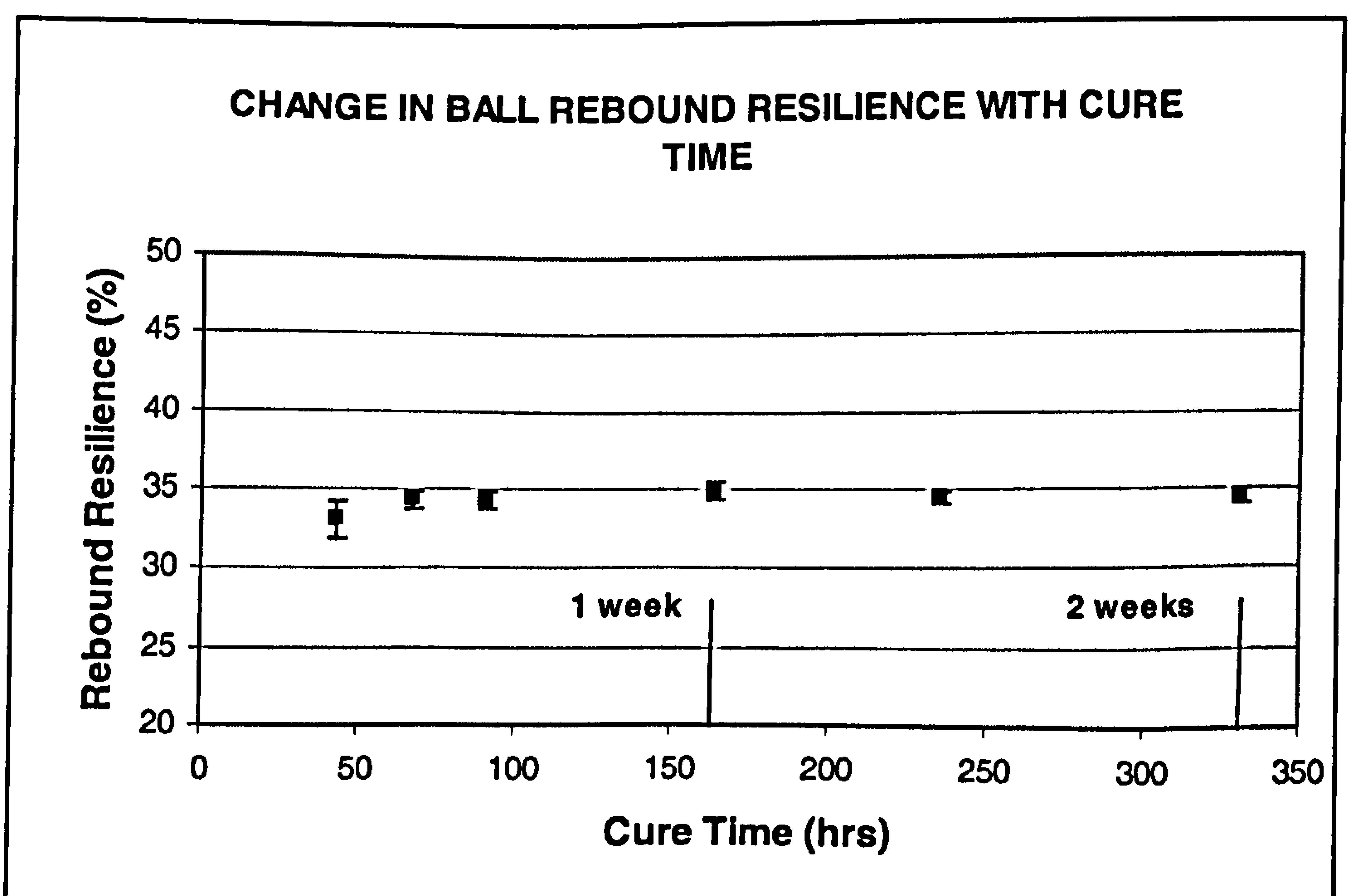
Wilson, J.F., Rochelle, R.D. and Bischoff, J.E. (1997) *Identification and Correlation of Human Footfall Load Parameters Using Multivariate Analysis*, Journal of Biomechanical Engineering, 119, pp. 115-123

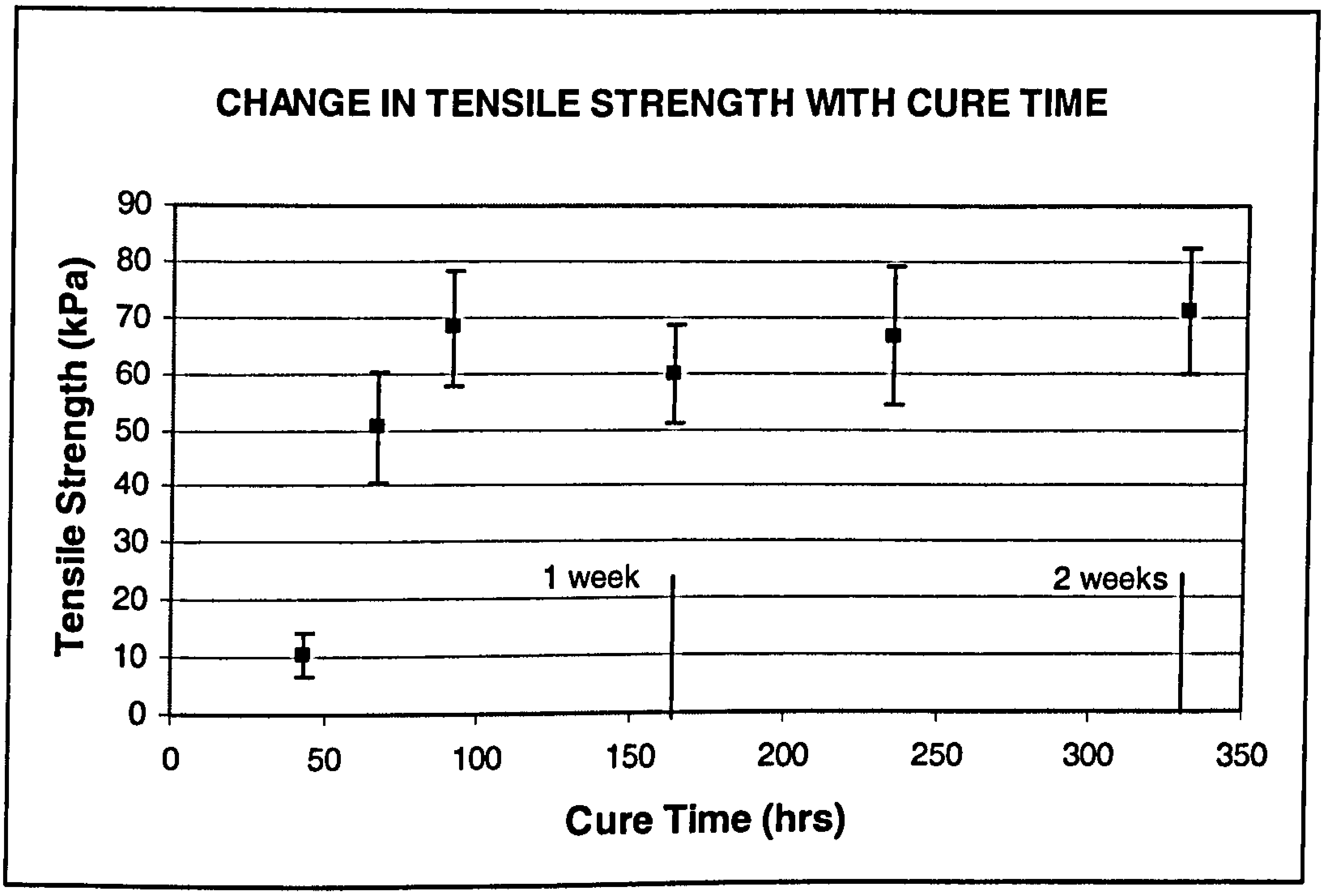
Winter, D.A. (1980) *Overall principle of lower limb support during stance phase of gait,* Journal of Biomechanics, 13, pp. 923–927

Young, C. (2006) *Mechanical and Perceived Behaviour of Synthetic Turf Field Hockey Pitches*, PhD Thesis, Loughborough University, Loughborough, UK

APPENDIX 1
CHANGE IN SHOCKPAD MECHANICAL PROPERTIES WITH CURE TIME






CHANGE IN TENSILE STRENGTH WITH CURE TIME
Tensile Strength (kPa)
90
80
70
60
50
40
30
20
10
0
1 week
2 weeks
0
50
100
150
200
250
300
350
Cure Time (hrs)