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SCHOOL OF CIVIL ENGINEERING



**CHARACTERISATION OF IMPACT ABSORBING
ASPHALT**

by

Toby Mark Singleton

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SYNOPSIS

The intention of this project was to investigate a material that could provide an impact absorbing layer that had the potential to reduce injury, through use or accident, for a sports or safety surface. The method adopted was to replace proportions of aggregate particles with recycled crumb rubber in a bituminous mixture containing bitumen modified with a styrene-butadiene-styrene (SBS) polymer. The rubber particles constitute the larger particles of a continuous graded mixture and act as elastomeric inclusions, making the material 'bouncy' enabling it to absorb impact forces. The aggregate particles provide the material with a degree of resilience, stiffening the material matrix. The intention of using a SBS polymer modified bitumen (PmB) was that it can withstand permanent deformations because of its high degree of elasticity and will therefore maintain a bound material under impact. The reason the project has concentrated on a SBS PmB was because the constituent materials are specified within the patent for the material. The technology has been shown to provide an impact absorbing layer that can be adjusted in terms of mixture design to suit different impact absorbing criteria. The material produced is termed Impact Absorbing Asphalt (IAA).

IAA has many potential applications and to date has been used as a surface layer for play areas and a shock-pad underneath artificial sports turf. This thesis is concerned with the use of IAA in these two particular applications and investigates the criteria required for it to perform as a viable product. The design criteria for sports and safety surfaces require that the material performs in a number of tests defined by different sporting and governmental bodies. The most common is the impact attenuation test, which assesses the ability of the material to absorb impact as a measure of safety. Other design criteria include friction, permeability and durability.

Preliminary testing on the original mixture design showed that the material provided adequate performance for all of the design criteria except durability. In-situ trials of the material as a surface layer for a safety surface demonstrated that the material frets under mechanical wear, essentially leaving loose particles on the surface. This was judged to be a major problem and for the material to be a good alternative surface to

conventional bituminous materials in playgrounds, the problem needed to be investigated and solved.

It was discovered, through simulation of in-situ production, that short-term ageing was reducing the ability of the material to bind together, effectively reducing the effect of the binder. This led to the conclusion that an interaction between the rubber and the bitumen was taking place, especially at elevated temperatures, which was reducing the mechanical durability of the material.

Curing tests of rubber in bitumen have indicated that portions of the bitumen diffuse into the rubber causing the rubber network to expand and swell. The mechanical testing of the residual bitumen, collected after the curing tests, shows that the rheological and cohesive properties are affected through the interaction. The change in these properties has been attributed to the change in bitumen constitution with the lighter molecular weight fractions being absorbed by the rubber.

The effect of the interaction on the material was then assessed using the Abrasive Wear Test, developed to empirically measure the effect of short term ageing and alterations in mixture design on the mechanical durability of the material. The effect of short term ageing was found to reduce the mechanical durability of the material. An impact attenuation test was used to ensure that changes made to the mixture design to improve the mechanical durability did not adversely affect the impact absorbing properties of the material.

Practical guidelines have been produced, based on the research carried out in this thesis out giving details of the main considerations when designing and constructing IAA. In addition a predictive model on the impact performance of IAA as a layer for an artificial sports turf pitch has been developed.

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DECLARATION

The work described in this thesis was conducted at the University of Nottingham, School of Civil Engineering between July 1997 and June 2000. I declare that the work is my own and has not been submitted for a degree of another university.

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1. INTRODUCTION

In 1993 the British Sport Council published results on a national survey of sports injury incidence. They predicted a national annual cost of half a billion pounds due to sports induced injury (Nicol, 1993). Approximately one third of these costs are due to sprains and strains that are influenced by the type of playing surface. It has been demonstrated that a reduction of the incidence of these types of injury has occurred since the introduction of shock absorption into footwear. Therefore, it is likely that increasing the shock absorption of surfaces will also lead to a reduction in injury (Nicoll, 1993).

Traditional artificial sports surfaces comprise either concrete or bituminous base overlaid with a synthetic grass carpet. Recently developments have been made to increase the shock absorption by placing a resin bound rubber shock pad underneath the carpet. These have become successful and now represent the standard. However, they are expensive and a more cost effective replacement needs to be researched. Another application for a shock absorbing surface is in play areas in schools and parks. Present applications are either expensive (resin bound rubber tiles) or inferior (tree bark), so an alternative that is cost effective, easy to construct and durable is needed.

One alternative is to replace a proportion of aggregate in a conventional bituminous material with recycled crumb rubber. The rubber particles act as elastomeric inclusions in the material matrix that impart a shock absorbing property upon impact. A patent was developed for the material using bitumen modified with the styrene butadiene styrene (SBS) polymer as the binder. The technology was called Impact Absorbing Asphalt (IAA). The purpose of the project was to investigate the suitability of IAA as an alternative sports and safety surface to present products.

1.1 Sports and Safety Surfaces

A sports or safety surface can be defined as a prepared area of land including surfaces formed with vegetation or loose particles for a natural playing surface or layers of processed material to form a continuous or bound surface for artificial or man-made

sports surfaces. Artificial surfaces can be defined in two main areas: indoor and outdoor. The main distinction is that outdoor surfaces have to be resistant to weathering and the top layers have to be designed in conjunction with the substrate layers to produce adequate drainage. Regardless of the difference in materials the surface, either designed for sporting activities or as a safety surface, has to perform adequately to allow the discipline to be carried out uninterrupted and with no undue problems (Dury, 1979). The performance of the surface can be assessed through a number of different parameters;

1. Safety
2. Durability
3. Spin
4. Friction
5. Stiffness and Energy Absorption
6. Permeability

There are a number of other parameters considered such as colour, dimensions, sound absorption and cleaning but the main list contains the parameters that are measures of the mechanical performance of the surface.

The safety of a surface can refer to a number of different aspects including fire resistance, toxicity and the likelihood of the surface causing physical injuries. The types of injury associated with artificial surfaces can be from a number of different causes. Friction burns from sliding contact are associated with an abrasive surface and are especially common with sand filled artificial grass surfaces. Bone fracture from severe impact can occur on many surfaces and can be influenced by friction in that low friction can cause a fall. The occurrence of bone fracture is further enhanced when the surface is particularly hard and resilient, such as concrete. Harder surfaces may also be the cause of overuse injuries from repeated impacts that cause strain on bones, ligaments and muscles, a typical problem for road runners. Another common injury for many sportsmen and women is twisting of joints often occurring when the surface has either too much or too little skid resistance (Frederick, 1984).

The durability of the material often determines whether the surface is economic and will have a long life. Wear of the surface can occur through a number of mechanisms: environmental and mechanical. Environmental durability of the material refers mainly to outdoor surfaces that are exposed to rain, extremes of temperature and solar radiation and for the surface material to have a long life it must be resistant to degradation through these mechanisms. Mechanical durability refers to the ability of the surface material to withstand wear which can come from abrasion, tearing, impact and vandalism. It is essential that a surface can withstand these actions without deteriorating and requiring remedial work.

Spin and friction are interrelated in that both refer to the friction between the surface and another object. Spin, including rolling resistance, is determined by the friction between the surface and a ball and is therefore only relevant to surfaces that are to be used for bouncing and rolling of balls. Friction is more broadly related to the interaction between the foot and the surface. The desirable level of friction is one that provides enough traction to prevent slipping but not too high that will prevent foot movement. Friction is one property that can be greatly affected by the state of the environment, i.e rain.

The dynamic interaction between the person and the surface is complex and involves the stiffness of the surface, the energy absorbed through the impact and friction. The stiffness of the surface has to be balanced according to its uses for the surface to perform well. A surface with a high stiffness is 'hard' and can cause jarring to the user. A soft surface with a low stiffness can slow the user down, which is undesirable for a sports surface, but can be very desirable for a safety surface. Therefore, the desirable stiffness of the surface required is dependent on the activity it is to be used for. The energy absorbed through the impact is a measure of the amount the user rebounds from the surface and is a main consideration for the performance of the material for a ball sport where the amount it bounces affects the way the surface plays.

Permeability of the surface is an important parameter for outdoor surfaces. The permeability should be measured for the system, rather than just the surface layer. It is a particular concern for artificial surfaces where the frictional properties are affected considerably when water is on the surface, increasing the likelihood of slipping and

therefore reducing safety. If water 'ponds' on the surface, the continuity of play is disrupted, which is the reason why many sports events are called off due to water logged pitches. Essentially, a surface should have a method of removing water quickly and efficiently so that use of the surface is not disrupted. The two main methods are vertically through the pavement system, or runoff into drainage systems for an impermeable surface.

The parameters mentioned above have been considered for many years and performance tests have been developed to measure and assess the surface as either a safety or sports facility. Different sporting bodies and governments have adopted different tests for defining the performance of the surface relevant to their sport. One of the most popular tests is to measure the impact performance of the material due to the growing concern of overuse injury and accidental injury on artificial surfaces.

1.2 Impact Absorbing Asphalt (IAA)

Impact Absorbing Asphalt (IAA) is a relatively conventional continuously graded bituminous material with a proportion of the aggregate replaced by dry crumb rubber obtained from the recycling of truck tyres. It has many potential applications and to date has been used as a surface layer for play areas and a shock-pad underneath artificial sports surfaces. The technology adopted is similar to the generic dry process developed in the late 1960's in Sweden and traded in Europe under the name Rubit (Heitzman, 1989). Production of the material involves adding the crumb rubber to the hot aggregate prior to mixing with the bitumen. The material is then mixed and held at a high temperature until compaction, which is carried out using conventional paving techniques. The binder used for IAA is a bitumen, modified with styrene-butadiene-styrene elastomer (SBS).

The intention of this thesis is to outline the development of IAA as a sports or safety surface. Particular reference is paid to the impact absorbing characteristics, via an impact attenuation test, for the material used as a sports or safety surface and the mechanical durability, via an abrasive wear test, as a safety surface. The mechanical durability of the material has been a major focus of the development because initial trials of the material were found to fail through break up of the material matrix

leaving loose particles on the surface. Investigation of this phenomenon has concluded that there is an interaction between the crumb rubber in the mixture and the bitumen binder. The direction of the research has been to understand the reaction in order to improve the mechanical durability of the material. These developments have been hand in hand with the impact performance of the material, to ensure that changes to improve the durability have not reduced the impact absorbing characteristics that are the material's major advantage as a sports and safety surface.

The two major forms of IAA are 3/20 IAA; a surface material designed for play areas and 10/40 IAA; a shock pad layer for artificial turf pitches for sporting activities. The nomenclature refers to the nominal particle size and the nominal thickness of the layer, i.e. 3/20 is a continuously graded aggregate and rubber material with an average particle size of 3mm and is laid as a 20mm layer. The mixture designs for these are given in the Appendix.

1.3 Problem Statement

Preliminary trials of both materials presented some interesting problems. The first trial of 3/20 was laid in a school playground in Matlock, Derbyshire. The material was laid and compacted immediately, but after very little usage, the particles of the material worked loose and the material was fretting. A similar trial was carried out at a school in Redmile, Nottinghamshire and the same phenomenon occurred. Laboratory prepared specimens had displayed no failing of this nature and suggested that the initial reason for failure was through the production method of the material on site. Preliminary trials of IAA 10/40 were laid at Ballidon Quarry, Derbyshire. Fretting at this trial did not occur to the same degree as the IAA 3/20, but a few small pot holes formed very soon after construction. Again, laboratory produced specimens had not shown any degradation of this form. The failure due to fretting was severe in the IAA 3/20 so laboratory testing was carried out to simulate the field production of the material.

Field production of IAA is similar to a conventional hot bituminous mixture. The material components (aggregate, rubber and bitumen) are heated to temperatures in excess of 155°C and mixed at a plant. The mixed material is placed in insulated trucks

to maintain the temperature and is transported to site where it is spread out and compacted while it is still hot (155°C or above) and then allowed to cool. It is maintained at a high temperature so that the material is workable allowing it to be spread and compacted. The material is held at elevated temperatures whilst it is being transported for up to 6 hours and the simulation of this period is called short term ageing. To simulate the field production, short term ageing in the laboratory was carried out by mixing the material then, before compaction, holding the mixture at 155°C in a draft forced oven for up to 6 hours. After this the material was removed and compacted in the roller compactor in the laboratory. Inspection of the specimens that were short term aged in the laboratory showed similar failure mechanisms to the in-situ trials and it appeared that the longer the material was held at an elevated temperature, the poorer the compacted material held together and resisted fretting. Fretting of a bituminous material in-situ is usually an indication of poor compaction methods. This is also likely to be a reason for the in-situ failures of the trials, but the fact that the fretting is more severe as the material is further short term aged suggested that the primary cause was not the compaction methods.

1.4 Summary

A preliminary investigation carried out indicated that there is an interaction during short term ageing of the mixture that is increasing the likelihood of the material fretting. The first stage was to discover what was causing the fretting. A literature study on previous experience with rubber in bituminous mixtures suggested that the rubber absorbs fractions of the bitumen at elevated temperatures. Chapter 2 outlines the literature on the interaction between rubber and bitumen. Two of the components of IAA, namely the crumb rubber and the SBS polymer modified bitumen (PmB) are described and previous experience of adding crumb rubber to bitumen is outlined to aid in understanding the effect of the interaction of both constituents. This is followed in Chapter 3 with an experimental investigation into the interaction, describing swelling tests to show that the rubber is absorbing the bitumen and Chapter 4 investigates the mechanical testing of the residual bitumen to show that the interaction is altering the performance of the residual bitumen. This relates to the function of the bitumen as a binder in the IAA mixture being affected by the interaction leading to loss of cohesion/adhesion of the bitumen thereby explaining the reasons for it fretting.

Constituent analysis of the bitumen gives an indication of which components are being absorbed leading to possible solutions to the problems caused by the interaction.

Chapter 5 describes the experimental work in analysing the effect the interaction between the rubber and bitumen has on the fretting, which has been defined as the mechanical durability of the IAA material, by using the Abrasive Wear Test developed for this purpose. This is followed by Chapter 6 which presents a protocol for short term ageing and the results on the abrasive wear test. Alterations of the mixture design to improve the mechanical durability have been tried and are detailed.

Chapter 7 is an investigation into the performance of the material as an impact absorbing layer. The various tests available for quantifying the impact absorbing characteristics are analysed culminating in adopting the impact attenuation test. The development of the test procedure and apparatus for the impact attenuation test at the University of Nottingham is outlined to show that the developed test gives accurate results. The results from testing the impact absorbing properties of IAA are then presented in Chapter 8. Different mixture designs have been tested to assess the effect of rubber content, thickness, temperature, sub-base and other factors on the impact performance.

The penultimate chapter discusses the development of a design guide in the form of a set of practical guidelines. It details suggested production methods of the material at present and the mixture designs for both forms of IAA with adjustments for the impact performance depending on sub-base structure, substrate structure, rubber content, thickness and other parameters.

The final chapter suggests further areas of study for the material and a different approach to solving the fretting problem and concludes the major findings of this project.

2. REVIEW OF RUBBER-BITUMEN INTERACTION

2.1 Introduction

Early field trials of Impact Absorbing Asphalt (IAA) have shown that the material exposed at the surface has shown a tendency to fret leaving loose particles of rubber and aggregate. The onset of fretting is found to occur almost immediately upon construction and is due to loading (running and walking) on the surface. Fretting of conventional bituminous materials used as a road surface is an indication of the loss of adhesion/cohesion of bitumen with the aggregate (Scholz, 1995). It usually occurs after a long service life due to mechanical wear on the surface or chemical wear, generally caused by water ingress into the material. When fretting of a road surface occurs shortly after construction it is usually an indication of poor material compaction or of insufficient bitumen binder in the mixture.

Controlled compaction trials of IAA have been carried out in the laboratory at Nottingham. The slabs produced, where the mixed material has been held at high temperatures before compaction, have shown a loss of adhesion/cohesion indicating that poor compaction is not the sole factor that is affecting the durability of the material. Preliminary experiments have shown that the crumb rubber is absorbing a proportion of the bitumen causing it to swell. It is postulated that this absorption is reducing the amount of binder in the mixture and the cohesion and adhesion of the residual bitumen which reduces the durability of IAA. This is an important issue for the material and it is necessary to investigate the interaction between the rubber and the bitumen to aid in designing a more durable material. This chapter investigates previous research on the interaction between the crumbed rubber and bitumen, which are two of the main constituents in IAA.

The chapter will provide background information on the reaction taking place in IAA. Firstly, the two materials, crumb rubber and SBS PmB will be classified by summarising their production, chemical structure and physical appearance. The origin of crumb rubber is from used tyres and an explanation of the production of a tyre, specifically the rubber, is given for a description of its chemical and physical composition. The styrene-butadiene-styrene (SBS) polymer modified bitumen (PmB)

is made by blending bitumen with SBS polymer. Therefore, the origins and composition of the two materials are explained to generate a model for the chemical and physical structure of the SBS PmB.

Crumb Rubber Modifier (CRM) technology has been used in many applications for bituminous materials. Section 2.4 will explain the two main processes in utilising crumb rubber in bituminous materials, the Wet Process and the Dry Process, and their development. This area was developed mainly for road materials where the proportions of rubber added to the mixture are considerably lower than IAA. However, the development of these materials have illustrated problems that have also been found in IAA and which provide understanding of the interaction between the rubber and the bitumen.

The final section looks specifically at the diffusion of solvents into polymers. This supports the idea that proportions of bitumen are acting as solvent and diffusing into the rubber (polymer) causing it to swell. The rate of diffusion is affected by a number of parameters and past work has sought to develop rate equations for each of these parameters.

2.2 Crumb Rubber

Crumbed rubber is extracted by granulating used truck tyres using the Crackermill Process (Buncher, 1994). The Crackermill Process is a mechanical method that sequentially grinds the tyre into smaller particles. In the process, the wire and fabric that reinforce the tyre are gradually removed via electromagnets and flotation chambers respectively as the rubber particles are ground down. Truck tyres are crumbed by this method when they have been used past their life span. Truck tyres are preferred because they have a high ratio of rubber to fabric compared with conventional car tyres resulting in a higher productivity of crumbed rubber. However, the construction processes are similar for the two types of tyres and the reality is that both types of tyres are used in the crumbing process.

This section outlines the production of tyres that make up the primary resource of rubber in the crumb rubber used in IAA. The method of production is explained by

concentrating on the tyre structure and the types of rubbers used. The main point that should be noted is that the crumb rubber is produced from a large number of different tyres each consisting of different types of rubber, therefore forming a large range of rubbers in the crumb. A generic form of the crumb is postulated that can be used to model the physical chemistry of the crumb rubber and bitumen. This forms the background properties of the rubber to aid in the understanding of the interaction between the bitumen and rubber.

2.2.1 Tyre Production

Pneumatic tyres have been one of the most important developments in the last two centuries. In 1846, R.W.Thompson was granted a patent for an elastomeric air tube to be fixed onto a wheel to reduce the power to haul a carriage. This concept was refined in the 1880's where the first pneumatic tyre was developed for use on tricycles (Mark et al. 1994).

The discovery of vulcanisation by Charles Goodyear in 1839 enabled the tyre to evolve in the late 1800's from a rubberised canvas covering a rubber tube into the complex fabric, steel and elastomeric composite in use today. The production of the modern tyre is a complex process and differs from manufacturer to manufacturer (Mark et al. 1994). However, the process is common for all methods of production and will be regarded so for the purpose of this document.

A tyre is made up of a three main materials; elastomeric (rubber) compound, fabric and steel. The fabric and steel form the structural skeleton of the tyre with the rubber forming the "flesh" of the tyre in the tread, sidewall, apexes, liner and shoulder wedge (see Figure 2.1). The tyre skeleton consists of beads made of steel or fabric depending on the tyre application, which form the 'backbone' in the toe of the tyre. The beads are designed to have a low extensibility and provide reinforcement for the rubber tyre. The tyre has a series of reinforcing cords or belts that extend from bead to bead transversely over the tyre. The belts are made of nylon fabric or steel but more commonly both types are used. The rubber tread then covers the belts providing the contact area for the tyre on the pavement. The objective of the skeleton is to reinforce the tyre to allow it to perform well without excessively deforming.

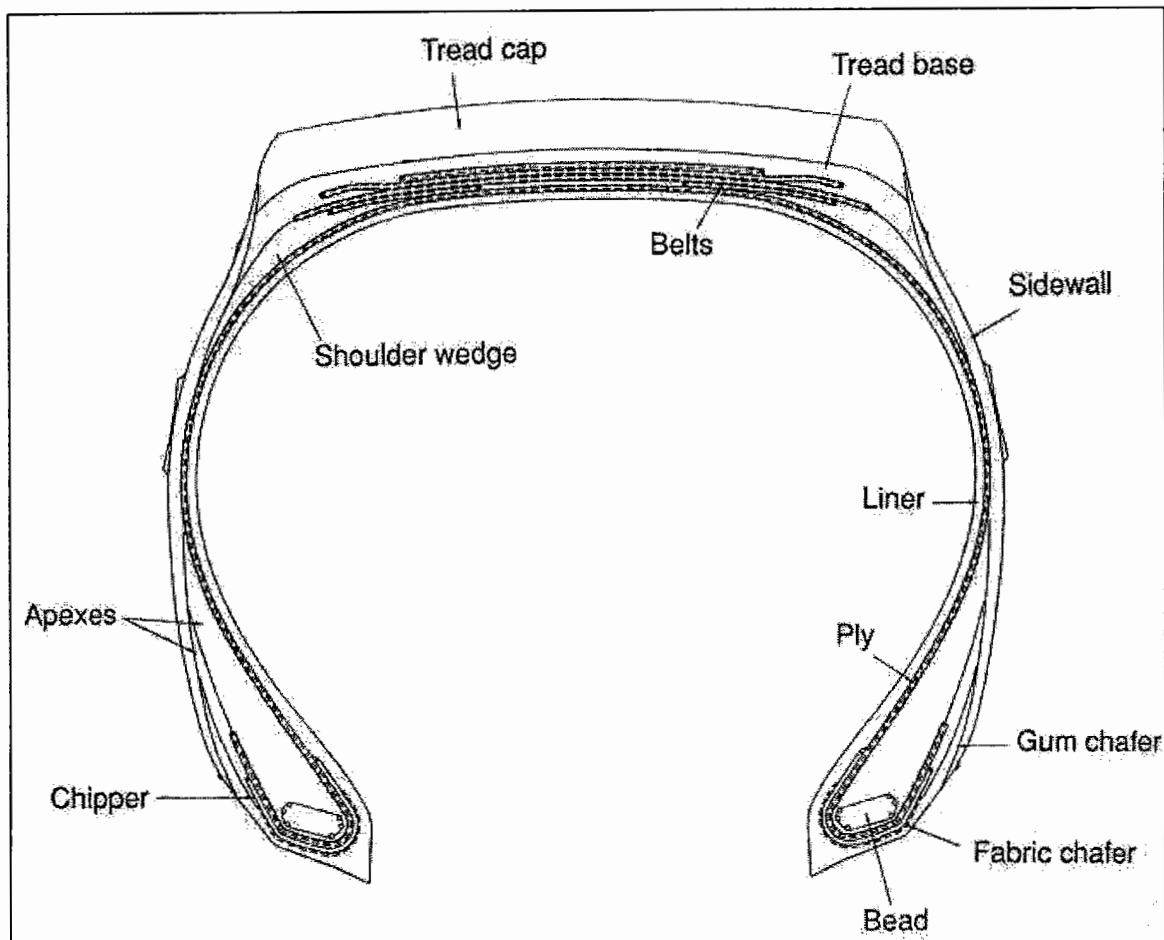


Figure 2.1 - A schematic showing the cross section of a typical truck tyre (Mark et al. 1994)

Tyre construction is a complex process of compounding the elastomer (rubber), processing the steel and fabric with the rubber, extruding the treads and side-walls and then curing the tyre under heat and pressure, known as vulcanisation. The next section will concentrate on the production and vulcanisation of the elastomer (rubber) as this is the main constituent that is of relevance to IAA.

2.2.2 Elastomer Production

The elastomer (rubber) component of the tyre is essentially a compound of a polymer network, filler systems, stabiliser systems and the base ingredients of vulcanisation. The polymer network is provided by an elastomer of which there are four types used in tyres:

1. Natural Rubber
2. Styrene-butadiene rubber (SBR)

3. Polybutadiene
4. Butyl rubber

Natural rubber is the main constituent of the radial truck tyre, especially in the apex and tread regions. SBR is the most common of the synthetic elastomers. All the elastomers consist of long polymer chains that are allowed to slide past each other upon stretching. This is a feature that gives the elastomer its characteristic ability to undergo large plastic deformations. A polymer is made up of a series of repeat monomer units of organic compounds linked together forming a chain. The monomer units primarily consist of carbon and hydrogen molecules. The consistency of natural and synthetic rubbers in this form can be likened to chewing gum. Therefore, they have very poor structural properties and it is necessary to treat the compounds to meet material property targets such as tensile strength and abrasion resistance required in tyres. Fillers, or reinforcement aids, such as carbon black, clays and silicas are added to the elastomer to meet some of the material property targets (Mark et al., 1994).

The structure of the polymer chains affect how it will degrade under certain conditions. In elastomers, such as natural rubber and SBR, the presence of the double carbon-carbon bond in the polymer chain makes it particularly susceptible to attack by oxygen and also thermal degradation. Oxidation of elastomers is accelerated by a number of factors including heat, sulphur, light, moisture and the swelling in oil or solvents. Therefore, during compounding of the rubber, an anti-degradant or stabiliser system is added to maintain the properties of the rubber by resisting oxidation and thermal degradation.

The fourth component of the rubber compounding system is vulcanisation. Vulcanisation describes the process where the physically soft compounded rubber materials or 'green' rubber, is converted into a high quality engineering product. The first process, developed by Charles Goodyear, consisted of heating natural rubber in sulphur. Essentially the same method is used today except many more synthetic rubbers have been developed and, in addition to sulphur, many other substances have been introduced as components of the curing (vulcanisation) system.

Vulcanisation can be defined as the process that decreases the amount of permanent deformation remaining in the rubber after removal of a deforming force (Mark et. al, 1994). It increases the elasticity while it decreases plasticity of the polymer. The process works by inserting cross-links between adjacent polymer chains in the compound. The cross-link can be of many forms, but the original was a single sulphur atom forming bonds with adjacent chains that reduce the ability of the chains to slide past each other. The vulcanising agents are added to the rubber compound prior to the heating (curing).

The tyre is made by constructing the skeletal support of steel and fabric which is then coated by a thin layer of 'green' rubber to provide direct rubber-rubber cohesion. The 'green' rubber compounds are then placed in the sections of the tyres. Different rubber compounds are placed in different sections of the tyre according to their desired properties. These are placed prior to the vulcanising process because the rubber is workable, once vulcanisation has occurred the rubber is very difficult to mould. The 'green' tyre is then placed in a pressurised mould, which defines the tread, wall thickness and shape of the tyre and heated to allow vulcanisation to take place (Blow, 1971).

Types of Rubber Compound

The different rubber compounds within each tyre are produced based on their desired mechanical properties. Table 2.1 illustrates the ingredients of typical tyre compounds.

Unfortunately, different tyre producing companies use different compounds and because of industrial competition it is difficult to determine the exact chemical makeup of each tyre. The re-treading of tyres further complicates the determination of the types of rubber in the crumb rubber.

**Table 2.1- Different rubber compounds within a conventional radial truck tyre
(Mark et al., 1994)**

	Tread	Side-wall	Wire Coat	Ply Coat
Polymer System	NR PBD S-SBR E-SBR	NR PBD	NR PBD	NR PBD
Filler System	SAF ISAF HAF	FF FEF GPF	HAF	HAF
Vulcanisation System	Semi EV	Adapted to polymer system	Conventional system	Conventional system Semi EV
Miscellaneous Components	Oils Waxes	Anti-degradants Waxes	Adhesion promoters	Adhesion promoters

Key

NR – Natural Rubber

PBD – Polybutadiene

S-SBR – Solution styrene-butadiene rubber

E-SBR – Emulsion styrene-butadiene rubber

SAF- Carbon Black (Particle size = 11-19nm)

HAF- Carbon Black (Particle size = 26-30nm)

ISAF- Carbon Black (Particle size = 20-25nm)

FF - Carbon Black (Particle size = 31-39nm)

FEF - Carbon Black (Particle size = 40-45nm)

GPF - Carbon Black (Particle size = 49-60nm)

Semi EV - Semi Ethylene Vinyl

2.2.3 Re-treading Tyres

The majority of tyres used for recycling in the crumbing plant have been re-treaded. The advised limit of retreading a tyre is twice (Mark et al., 1994). It is a more economical solution for tyre users to retread a tyre rather than replace it, therefore most tyres are re-treaded twice before being discarded and sent to the crumbing plant.

Re-treading a tyre makes use of the skeletal structure of the used tyre by removing the worn outer coating of rubber and replacing it. A mechanical buffing machine is used to grind away the remaining tread and side-wall, from the worn tyre. Care has to be

taken not to grind down to the belts as the bond between the existing rubber, fabric and steel must be maintained. A replacement 'green' rubber compound sheaf is placed over the buffed tyre and the re-treaded tyre cured inside a mould to produce a new tread and side-wall (Blow, 1971).

If this is carried out twice it is possible that each tyre that is selected for crumbing has three different makes of rubber as well as the different compounds from each section in the tyre. Therefore, a batch of rubber crumb contains a mixture of vulcanised natural and synthetic rubbers containing a number of compounds including carbon black and sulphur among many others. Structurally, the generic form can be categorised as a three dimensional network of cross-linked polymer chains. The cross linkages are formed in vulcanisation and can take the form of primary valence bonds connecting the chains directly, or an intermediate group or atom such as sulphur which is bonded to each of the two chains. This model will provide the basis of the analysis of swelling in bitumen.

2.3 Bitumen

Bitumen is manufactured from crude oil that originates from the remains of marine organisms and vegetable matter deposited on the ocean bed. Over millions of years, the matter is accumulated and through the immense weight of the upper layers the matter in the lower layer is compressed. Combined with heat from the Earth's crust, the matter forms crude oil that is trapped by impermeable rock forming large underground reservoirs. The crude oil can sometimes rise through faults in the layers above, coming to the ground surface where it was first discovered. Most crude oil is now extracted from large underground reservoirs by drilling (Whiteoak, 1990).

There are many sources of crude oil and only a few of these produce a suitable raw material for bitumen. Bitumen is extracted from crude oil by a refining process. British Standard 3690: Part 2 (1989) defines bitumen as 'A viscous liquid, or a solid consisting essentially of hydrocarbons and their derivatives, which is soluble in trichloroethylene and is substantially non-volatile and softens gradually when heated. It is black or brown in colour and possesses waterproofing and adhesive properties. It is obtained by refinery processes from petroleum, and it is found as a natural deposit

or as a component of naturally occurring asphalt in which it is associated with mineral matter.'

2.3.1 Bitumen Constituents and Structure

Bitumen is a complex mixture of organic molecules. The molecules comprise mainly hydrocarbons with minor amounts of functional groups such as oxygen, nitrogen and sulphur. As bitumen is extracted from crude oil, which has many different compositions according to its origin, the precise breakdown of hydrocarbon groups in bitumen is difficult to determine. Perhaps the simplest model for the bitumen composition is to break it into four main chemical types used to classify the make up of the bitumen (Airey, 1997):

- Asphaltenes
- Resins
- Aromatics
- Saturates

Asphaltenes are black or brown amorphous (without shape) solids. They are highly polar, complex materials of high molecular weight (between 1,000 and 100,000). Within a medium they have a tendency to associate together to form micelles with a molecular weight between 20,000 and 1,000,000. Asphaltenes typically constitute 5% to 25% of the bitumen. The molecular weight relates to the size of each molecule, so the higher the molecular weight, the larger the molecules.

Increasing the asphaltene content in bitumen produces a harder, less fluid bitumen. The structure of asphaltenes is not fixed; on heating, the gel structure of the micelles is broken down and reformed on cooling. For prolonged heating the asphaltene micelles may break down. Therefore, it is not unusual for the molecular weight of bitumen to decrease after heating.

Resins are black or brown solid or semi-solid highly polar molecules. The high polarity makes the resins very adhesive. The molecules have a molecular weight

between 500 and 50,000. The resin part of the bitumen also acts as a peptising agent for the asphaltenes, therefore an increase in resin results in a solution (sol) structure whereas a reduction forms a gelatinous (gel) structure in the bitumen.

Aromatics have the lowest molecular weight and form the major proportion of the bitumen (40-65%). They have a very low polarity and form a dark brown viscous liquid that acts as a dispersion medium for the asphaltenes in the bitumen and have a molecular weight between 300 and 20,000.

Saturates are straight branch chain aliphatic hydrocarbon molecules. They are non-polar viscous oils, straw or white in colour and form between 5% and 20% of the bitumen (Whiteoak, 1990).

Resins, Aromatics and Saturates form the maltene fraction of the bitumen.

The structure of bitumen is generally regarded as a colloidal system (Girdler, 1965) consisting of high molecular weight micelles (asphaltene) dispersed in a lower molecular weight oily medium (maltenes). The micelles are considered to be asphaltene clusters with a layer of high molecular weight resins surrounding each cluster that act as a solvating medium. The micelles are then dispersed by the solvent aromatics.

Solution (sol) bitumen is one that is rich in aromatics and resins that are able to fully peptise and disperse the asphaltene molecules in the bitumen. Gelatinous (gel) bitumen has insufficient aromatics and resins allowing the asphaltenes to associate further into larger micelles. This results in bitumen with a high viscosity that is less workable. A high saturate content can also result in a gel structure because it limits the ability of the aromatics and resins to dissociate the asphaltenes.

There are other models that have been developed to help define bitumen structure, Pfeiffer and Saal [1940] suggested that the bitumen was made up of dispersed phases composed of an aromatic core surrounded by layers of less aromatic molecules. In their model there are no distinct boundaries between the different chemical phases, but a continuum from low to high aromaticity. Another model was developed through

work on the Strategic Highways Research Program (SHRP) in the United States [Branthaver et. al. 1994]. This was a conceptual model referred to as a microstructural model. This suggested that the bitumen structure is based around microstructures (comprised of polar, aromatic, asphaltene - like molecules that tend to form associations) dispersed in a bulk solvent consisting of relatively non-polar, aliphatic molecules. These represent a couple of structural models for bitumen, illustrating that the structure of bitumen is not fully understood and there are different ways to treat it. For the purposes of this literature, the bitumen will be treated as a colloidal system made up of the four main chemical compositions but the findings can be related to other structural models.

2.3.2 Modified Bitumens

In many occasions, bitumen is modified by addition of either liquid or solid. The bitumen can be modified to improve the material properties for a particular application. The 'additives' can be classed into five main groups:

- inert fillers (limestone filler, silica and gypsum, etc.);
- mouldable fillers (sulphur, bitumen and wax, etc.);
- chemical agents (wetting/adhesion agents, etc.);
- solvents (including hydrocarbon extracts);
- polymers, (ethylene vinyl acetate (EVA) and styrene butadiene styrene (SBS), etc.)

This section will concentrate on one particular type of modified bitumen; SBS polymer modified bitumen (PmB). Styrene-butadiene-styrene (SBS) is a synthetic thermoplastic elastomer used in many applications such as in the soles of running shoes as well as an additive to bitumen. SBS PmB has improved flow resistance and flexibility at low temperatures compared to a straight run bitumen.

Elastomeric Modification

Styrene-Butadiene-Styrene (SBS) is a styrenic block copolymer made by successive polymerisation of styrene-butadiene-styrene monomers. Polymerisation is the production of a long chain molecule made up of simple repeat units, in this case, SBS. As well as linear copolymers, blocks of copolymer can be produced by polymerising a styrene-butadiene monomer. These are known as branched or radial copolymers and are shown schematically in Figure 2.2.

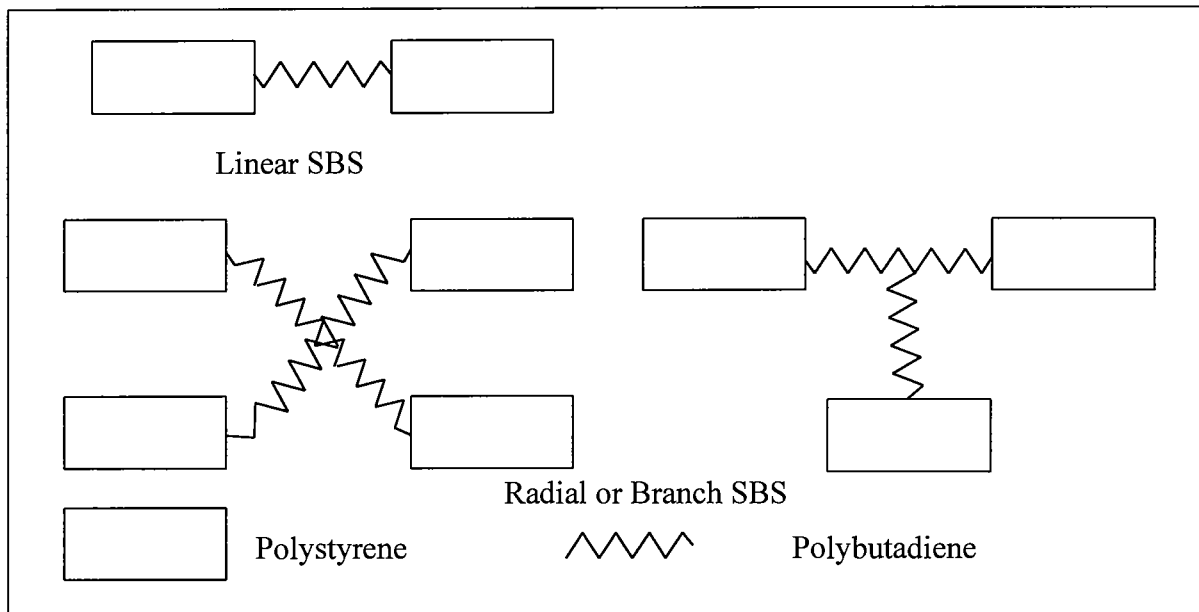


Figure 2.2 - Schematic Models of SBS Polymers (Whiteoak, 1990)

The SBS modified bitumen used in IAA contains only linear SBS copolymers. These polymers comprise long chains of monomer blocks between 10,000 and 100,000 in number. The relative sizes of these blocks determine particular properties of the grade of the SBS polymer (Morgan and Mulder, 1995).

As mentioned earlier, SBS is a thermoplastic rubber. The characteristics of a thermoplastic material are that at ambient temperatures it maintains its high strength and elasticity. This comes from physical cross-linking of the polymer blocks in a three-dimensional network. Cross-links form because the butadiene and styrene are incompatible and each try to form links with their own block. The styrene is referred to as the end-block and provides the strength of the material and the butadiene, the mid-block, contributes to the elasticity of the material. At temperatures above 100°C, the polystyrene softens and the links weaken and can even break under stress. The material begins to behave as a viscous liquid, a property that allows it to be blended

into bitumen. Upon cooling, the links reform and the strength and elasticity is restored, thus the material is thermoplastic (Morgan and Mulder, 1995).

SBS rubber granules (5mm diameter) are added to bitumen at a temperature between 165°C and 185°C and blended using a high shear mixer that grinds the rubber into smaller particles. On addition of the SBS, the polymer absorbs the maltene fraction of the bitumen causing it to swell. The polymer can swell to about 6-9 times its initial volume. The swelling and extension of the rubber at contents of 4-8% rubber is sufficient to form a two phase system consisting of a continuous network of rubber with the bitumen dispersed within the rubber network. This is a desirable effect and time is allowed for swelling during blending.

2.3.3 Effect of Bitumen Constitution on SBS Bitumen Blends

As discussed earlier, the composition of bitumen has an effect on its mechanical performance. The aromatics and saturates are viewed as the carriers for the polar aromatics, i.e. the resins and the asphaltenes. The polar aromatics are responsible for the visco-elastic properties of the bitumen at ambient temperatures due to the large structures, i.e. micelles. The degree to which these structures form is dependent on temperature, molecular weight distribution, concentration of asphaltenes and resins and on the concentration of the solvents in the form of aromatics and saturates in the maltene phase.

It is important that the bitumen blended with the SBS polymer is compatible so that the balance of asphaltenes and maltenes is maintained to enable the bitumen to perform (Whiteoak, 1990). Research by Vonk and Bull (1982) has shown that when the polymer is added to the bitumen, it absorbs, almost proportionally, all the components apart from the asphaltenes.

A bitumen/polymer blend is defined as compatible if the mixture is stable at high temperatures during storage, without stirring and compatible at in-service temperatures (Morgan and Mulder, 1995). If the mixture is not stable, phase separation will occur. When viewing a film of bitumen under a microscope, a compatible blend has a homogenous 'sponge-like' structure made up of the two phases

of polymer network dispersed by bitumen. An incompatible system is a coarse and discontinuous structure caused by a greater interaction of asphaltenes (Figure 2.3). An incompatible bitumen generally has inferior long term performance and elasticity because the effect of the polymer is reduced (Morgan and Mulder, 1995).

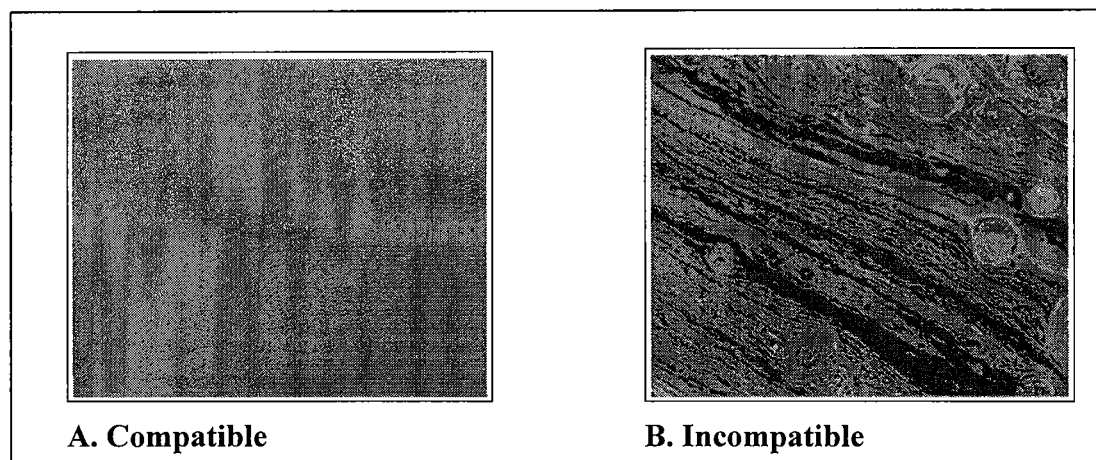


Figure 2.3 - Photomicrographs of bitumen/SBS blends (Morgan and Mulder, 1995)

The compatibility of the blend is dependent on a number of factors;

- the amount and size of the asphaltenes
- the amount and size of the polymer molecules
- the aromaticity of the maltenes phase

If the asphaltene content in the blend is too high, the loss of maltenes to the polymer that solvate the asphaltenes, causes larger micelles to form allowing gelation to take place in the bitumen blend making it unworkable. A low asphaltene content is more desirable as this allows a beneficial interaction between the polymer and the asphaltenes, whereas for high asphaltene content the asphaltenes accept too large a proportion of the maltene phase reducing the amount of polymer in the continuous phase (Morgan and Mulder, 1995).

If the molecular weight of the polymer is similar to or greater than that of the asphaltenes, the polymer more readily accepts the maltene phase, which reduces the solvency power for the asphaltenes. This allows the asphaltenes to precipitate and form micelles causing phase separation and an inhomogeneous mixture. In bituminous road pavement materials where phase separation has occurred when using

SBS PmB, the polymer phase will rise to the top and the asphaltene phase will sink. The top section becomes soft and elastic and the bottom section becomes hard and brittle (Morgan and Mulder, 1995).

If the aromatic content of the bitumen is too high, the polymer domains can be weakened leading to a more fluid material. Conversely, a low aromatic content reduces the ability of the polymer to form a continuous phase in the bitumen. This outlines the balance that is required within the bitumen to assure a compatible bitumen blend. Further addition of a polymer will cause an imbalance in the bitumen blend making it incompatible.

The constitution of the bitumen must be balanced for it to be compatible as a polymer modified bitumen. If this balance is altered by the addition of rubber, say, then it stands to reason that there is a possibility that the bitumen-polymer blend will become incompatible. This may be occurring in the IAA mixture, causing a change in constituents of the bitumen making the modified blend incompatible.

2.4 Applications of Crumb Rubber in Bituminous Mixtures

Research into improving the performance of bituminous binders by the addition of natural and synthetic rubbers has been carried out for over a century. Historically, the use of rubber as a modifier of bitumen is to improve the elasticity of the binder (Heitzman, 1991). The use of recycled scrap tyre as a modifier for bituminous binders has been under development for the last 30 years and for the last 15 years the emphasis for the modification of bituminous binders and mixtures has been seen as a way to recycle scrap tyres.

The addition of scrap tyres to bituminous binders or mixtures is generally termed crumb rubber modified (CRM) technology. There are two main categories of CRM technology defined on the basis of their production; the **wet process** and the **dry process**.

The **wet process** defines any method that blends crumb rubber with bitumen before incorporating the aggregate in the mixture. It is a similar method of production to that

of SBS PmB. Charles McDonald, a materials engineer for the City of Phoenix, developed the wet process in the early 1960s. The product from the wet process is termed **bitumen-rubber** (Epps et al 1992).

The **dry process** involves addition of crumb rubber to the aggregate before mixing with bitumen. The product is usually termed a **rubber-modified bituminous mixture**. This process has seen limited use with hot bituminous mixtures, whereas the wet process has been applied for crack sealants, surface treatments and hot bituminous mixtures.

2.4.1 Wet Process

The wet process blends crumb rubber with hot, liquid bitumen and an interaction between the two materials takes place termed the **rubber-bitumen interaction** (Takallou, 1988). The interaction is affected by a number of variables specifically blending temperature, blending time, type and amount of mechanical mixing, crumb rubber type, size and specific surface area of the crumb rubber and the type of bitumen. Heitzman (1991) suggested the reaction to be the absorption of aromatic oils from the bitumen into the polymer network of the natural and synthetic rubber from the crumb rubber.

The wet process is used to produce modified bitumen similar to SBS PmB defined in Section 2.3.2. Production consists of blending crumb rubber with bitumen and allowing the reaction between the two materials to take place. The blending process must control the proportion of the rubber (in the form of powder, granulated or both) added to the bitumen. The reaction tank must maintain a uniform temperature and a uniform blend to enable an even reaction within the blend. When the modified bitumen is transferred to its desired application, special pumps are required to ensure a uniform accurate binder is discharged for mixing (Heitzman, 1991).

Bitumen-rubber has a number of applications. McDonald developed the wet process to produce a highly elastic maintenance surface patch called a stress absorbing membrane (SAM) (Heitzman, 1991). The technology has also been used for crack and joint sealants because of its high elasticity. The major use of the bitumen-rubber is in

hot bituminous mixtures as a modified binder. Typically, the modified bitumen contains between 10-25% rubber by mass of the bitumen (Green and Tolonen, 1977). The crumb rubber is of the form of granules or fine powder between 2mm to 200 μ m (Takallou, 1988). Compared to conventional bitumen, the performance of bitumen-rubber displays an increase in the viscosity at mixing and operating temperatures. This indicates a flattening of the temperature-viscosity curve, thus reducing the effect of temperature on the in-service performance of the pavement. Generally, small granules (<800 μ m) are used because rubber particles any larger in the bitumen blend have been found to increase the variability in the mechanical performance of the bitumen rubber because the blend becomes inhomogeneous (Heitzman, 1991).

The use of the McDonald Technology for paving materials has been researched in a number of states in the US. Spurred on by legislation introduced in 1989, which dictated that recycled crumbed rubber had to be utilised in road pavements, investigations have been carried out by a number of parties to develop pavement mixture designs for bitumen-rubber. The wet process has become a far more popular method for using recycled crumb rubber because the conventional Marshall and Hveem mix design procedures have been successfully used with hot bituminous mixtures that utilise the bitumen-rubber. As a general rule, mixture designs have shown that mixtures using bitumen-rubber require between 1-2% more binder because the reaction between the bitumen and the rubber increases the viscosity of the bitumen (OSU, 1997).

Construction of modified hot bituminous mixtures is typically the same as conventional paving procedures. The mixing and laying temperatures are slightly greater due to the increase in binder viscosity. Pneumatic tyre rollers are not used for compaction because the bitumen-rubber tends to stick to rubber materials. Steel-wheel drum rollers have been successfully used, with some liquid detergent added to the drum water to help lubricate the drum.

The ability of the CRM to enhance the performance of the binder in the pavement is dependent on the compatibility between the bitumen and the rubber. An investigation carried out by the Western Research Institute in the USA showed that the amount and

type of carboxylic acid content in the bitumen affected the rheology of the bitumen-rubber blend. Therefore, the acid content and type may have an influence on the compatibility of the bitumen and rubber (OSU, 1997).

One of the major problems addressed by Takallou and Sainton (1991) was that the rubberised binder has to be used within hours of its production. Therefore, specialised equipment is required to produce the material on site increasing the cost of using CRM bitumen. In his research Sainton discovered that the chemical reaction between the rubber and the bitumen continued after blending while the material was kept at storage temperature (200°C). Rheological testing on the bitumen showed that the viscosity of the bitumen rubber reached its maximum after 45 minutes at 200°C, remained high for 1-2 hours and then decreased (see Figure 2.4). The reason for this was assumed to be reversion of the crumb rubber in the bitumen causing degradation of the binder. Reversion is the term applied to the loss of network structures developed in vulcanisation, i.e. the bonds with the polymer and sulphur are broken reducing the polymer to its original structure. It is caused by over-cure or thermal ageing and is most severe at temperatures above 155°C.

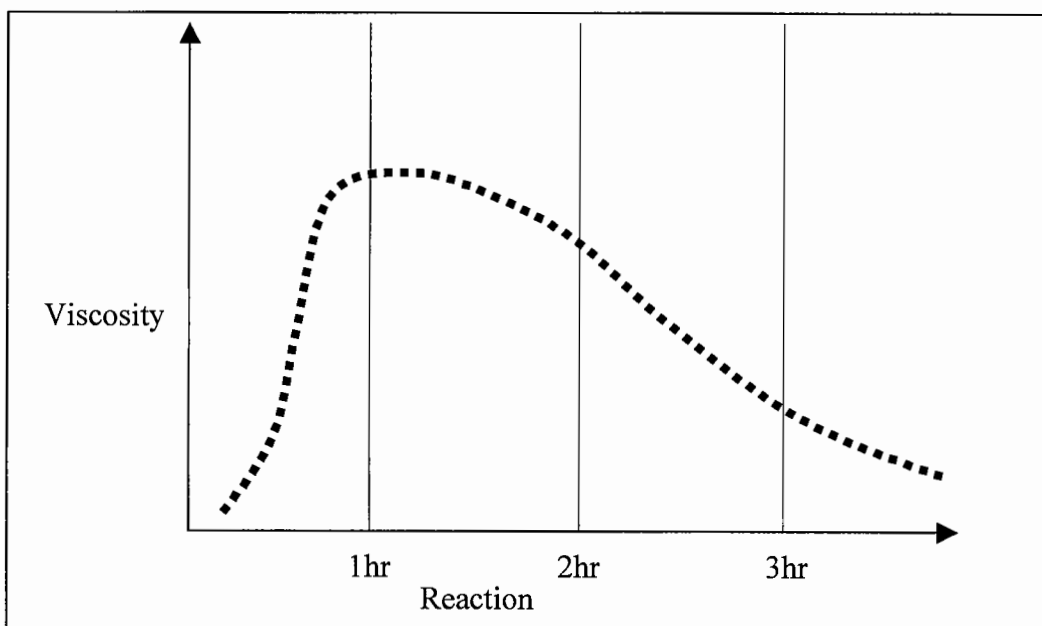


Figure 2.4 - Viscosity evolution for rubber-bitumen maintained at mixing temperature(200°C) (Takallou and Sainton, 1991)

Takallou and Sainton carried out a series of experiments to investigate the effect of crumb rubber content, oil extender and a catalyst on the storage time. It was found

that for bitumen with 10% crumb rubber, 6% oil extender and 2.5% catalyst by mass, the storage time was increased to 8 days instead of 1-2 hours. The catalyst added was selected from ethylenically unsaturated polymers or copolymers that have been recommended for sulphur-vulcanised bitumen intended for road surfacings. Its particular use is to reduce reversion of the rubber. This indicates that reversion of the rubber is having an impact on the properties of the blend.

The mix design using bitumen-rubber has come under scrutiny recently because of the discovery that the acid content has a dramatic effect on the binder rheology. Although, the effects on the mixture may not be dramatic it is difficult to overlook when developing a mixture design. Therefore, current research in developing mixtures has been held up (OSU, 1997).

2.4.2 Dry Process

The dry process was developed in the late 1960's in Sweden and was traded in Europe under the name Rubit. The Swedish technology was patented in the US under the name PlusRide in 1978. The principal highway agency that developed and utilised the system was the Alaska Department of Transportation (ADOT) (Heitzman, 1991).

The basis of the dry process is to use the crumb rubber as part of the aggregate. Coarse granulated rubber is added to the aggregate before addition of the bitumen. This is the process utilised for production of IAA. The dry process encompasses any method of adding crumb rubber directly to a hot bituminous mixture process. The product is a rubber-aggregate mixture and during production some reaction is known to take place. The degree of reaction is determined by the gradation of crumb rubber (Buncher, 1994). However, evidence from work carried out by Green and Tolonen (1977) has shown that the degree of reaction is also affected by the time the mixture is held at mixing temperature, the proportion of rubber to bitumen and the type of bitumen. Typically 3-4% of 2-6mm crumb rubber particles by total mass are incorporated into the aggregate. The bitumen will therefore be modified a small amount. However, this has been previously deemed unimportant to the properties of the material because the grading of crumb rubber is large and thus the specific surface

area is low reducing the rate of reaction between the rubber and bitumen in comparison to the wet process (Takallou, 1988).

Trials on rubber modified pavements have shown that in comparison with conventional pavements, the fatigue life is improved, however sometimes this has been at the cost of fretting. Alaska DOT discovered that one of the major advantages of the material was that because of the flexibility of the material when laid, trafficking helped to break up ice that formed on the road surface (Takallou, 1991).

Research has been carried out into the effect of the grading of aggregate and rubber on the performance of the material (Takallou, 1988 and 1991). Usually, a gap-graded aggregate is utilised with the rubber aggregate filling in the 'gap'. However, the inclusion of specially graded aggregates increases the cost of production.

The dry process has been a far less popular method than the wet process for utilising recycled crumb rubber over the past 20 years. Reasons for these differences are cost, construction difficulties and poor reproducibility associated with the dry process. The increase in cost over conventional paving has been due to a required increase in bitumen content, a unique gap graded aggregate, increase in mixture temperature and different techniques for construction. Essentially the main difference in construction is the introduction of a third material into the batch mixer plant. Often this has to be carried out by hand, tipping the rubber in to the batch mixer from bags. A continuous batch plant was used but difficulty came in assuring a consistent product because proportioning of the mixture contents was difficult to control (Heitzman, 1991).

The first product used in the US was PlusRide, adapted from the Swedish technology. PlusRide was a modified gap-graded mixture. The mixture design did not follow conventional mix designs but was designed to modify the stability of a gap-graded aggregate with the elastic properties of the crumb rubber and also some bitumen modification due to the interaction between the rubber and the bitumen. Conventional mixture design procedures such as Marshall stability and flow could not be used because the stability of PlusRide was lower than conventional mixtures and the flow was higher. The critical value was shown to be low percentage air voids. Therefore,

the optimum bitumen content was determined by a target air void content between 2-4%.

To try and reduce the cost of producing PlusRide, Takallou (1988) developed a rubber modified bituminous mixture using a general aggregate grading referred to as the TAK System. This utilised a constant aggregate grading with two grades of rubber. A fine powder crumb rubber was added to react with bitumen as a modifier and coarse crumb rubber to act as rubber aggregate. The system specified a maximum 3% by mass of rubber of the total weight of the mixture. A catalyst was added to achieve maximum swelling of the rubber before the material was laid. The system was successfully constructed for two demonstration projects in Ontario, Canada and preliminary tests showed the material to be performing as well as conventional systems.

2.4.3 Summary

Previous work on crumb rubber in bitumen has shown that the rubber reacts with the bitumen. The wet process utilises this reaction to increase the viscosity and elasticity of the binder. Some work has been carried out to investigate the factors that affect the rubber-bitumen reaction. However, this was done in reference to the wet process where the rubber is fine enough to become part of the bitumen structure. The dry process uses larger particles of rubber and most of the previous work has considered the reaction between the rubber and the bitumen to be negligible. Therefore, mix designs using the dry process have been based on the rubber being part of the aggregate system in the mixture, not the bitumen.

The preliminary work carried out in developing IAA has suggested that the reaction between the rubber and the bitumen is significant and has an effect on the performance of the bitumen. The next section will focus on the mechanics of swelling and diffusion in the rubber-bitumen reaction.

2.5 Interaction of Solvents and Bitumen with Rubber

2.5.1 Mechanism of Swelling

It has already been mentioned that the crumb rubber from tyres is a conglomeration of vulcanised rubber of slightly different chemical composition. However, all vulcanised rubbers according to Flory and Rehner (1943, Pt I) consist of a "three-dimensional network composed of very long rubber molecules laterally attached to one another at points along their lengths. The cross-linkages may consist of primary valence bonds connecting the chains directly, or of an intermediate group or atom such as sulphur which is bonded to each of the chains."

Swelling of polymers in solvents is well documented and it is known that polymers such as vulcanised rubber swell through imbibition of the solvent to a degree depending on the solvent and the structure of the polymer. The shape remains the same and the swollen gel exhibits elastic rather than plastic properties (Flory and Rehner, 1943, Pt II). The process of imbibition of the solvent into the polymer is known as diffusion. The measurement of diffusion has been found to be of use in describing structures of polymers and as a guide to their mechanical properties (Buckley et al. 1962, Pt I).

Flory and Rehner (1943, Pt II) investigate the diffusion of solvents into vulcanised rubbers. They developed an idealised model of the structure of vulcanised rubber to help describe the imbibition process.

Figure 2.5 illustrates the model Flory developed. A, B, C, D and P represent the cross-links between the polymer chains. Each point has four polymer chains intercepting as shown for P, so this diagram shows a single cell of a continuous three-dimensional network. The process of swelling can be visualised by imagining the solvent being absorbed by the polymer. The volume of the tetrahedral cells will increase proportionally, i.e. the cell will maintain its original shape but the points A, B, C and D will move further apart. Therefore, the shape of the network structure of the polymer is permanent through imbibition of a solvent because the skeletal structure of the polymer is not disrupted by the action of the solvent. Effectively the chains between the cross-links are stretched which causes a loss in entropy in the chain

configuration. Entropy is the energy associated with the probabilities of the molecular structure of a substance. Entropy is lost in the polymer structure when the chains are increased in length by swelling as it is assumed that the most probable configurations of the chains are when the polymer is not deformed. This is opposed by an increase in the entropy due to mixing of the solvent with the polymer entities. Therefore, when the entropies of mixing and chain configuration balance equilibrium swelling occurs. Therefore, the entropies of the rubber and the solvent/bitumen limit the amount of swelling.

Entropy is best understood from gases. When a gas is cooled down, work is put into the system. The total work done to the gas is always greater than the net work done in cooling the gas. In other words the system is never 100% efficient. The energy that is 'lost' is taken into the system as entropy, so when the system cools down, the entropy increases and the deviation of the molecular structures within the gas is reduced (Dugdale, 1996).

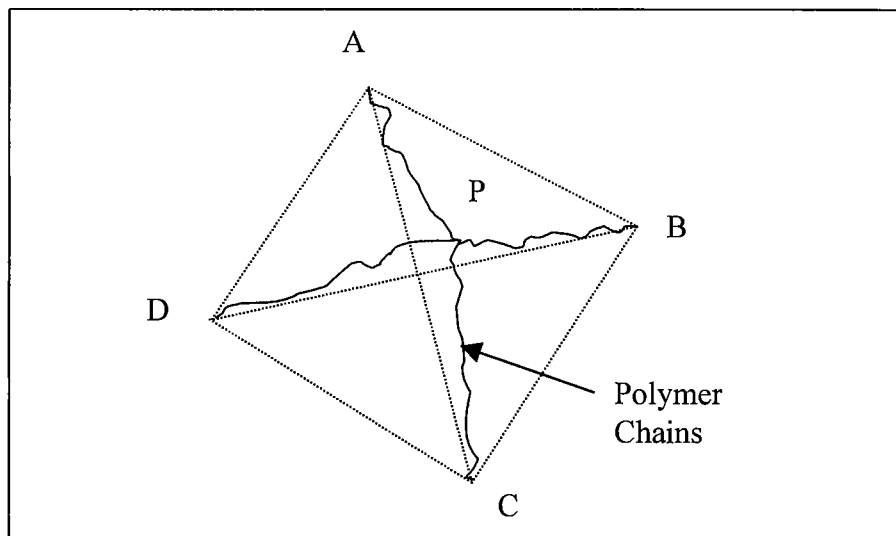


Figure 2.5 - A model for an elementary tetrahedral cell of tetrafunctional three-dimensional network (Flory and Rehner, 1943, Pt I)

Green and Tolonen (1977) when developing the wet process for rubber-bitumen investigated the diffusion of bitumen into crumb rubber. The main focus of the work was measuring the rate of swelling of the crumb rubber. The main purpose was to find suitable storage times for rubber-bitumen blends by measuring the rate of swelling and the maximum swelling of the rubber. Green and Tolonen found that the rubber in

bitumen-rubber swells at a rate determined by the temperature, rubber particle size and the concentration of bitumen.

2.5.2 Effect of Temperature

Temperature has two different effects on the swelling reaction between a solvent and vulcanised rubber. Firstly, as the temperature is increased, the rate of reaction increases. Secondly the increase in temperature reduces the amount of maximum swell of the vulcanised rubber.

The reason why the maximum amount of swell is decreased upon an increase in temperature can be illustrated by investigating the entropy of swelling. Flory and Rehner (1943, Pt II) equated the entropy of mixing with the entropy of swelling to develop the following expression for the extent of swelling in a polymer due to the imbibition of a solvent.

$$\frac{d(\ln v_2)}{d(\ln T)} = \frac{K}{2 \left[\left(\frac{5}{6} (K-1) - \frac{8}{9} v_2 - \frac{11}{12} v_2^2 - \dots \right) \right]} \quad 2.1$$

where;

v_2 = volume fraction of swelling polymer

$$K = A + \frac{2BV_1}{RT}$$

A, B = constants

V_1 = total volume of solute

T = absolute temperature

R = gas constant

For small values of K and high degrees of swelling this expression approximates to;

$$\frac{d(\ln v_2)}{d(\ln T)} \approx - \frac{3K(1-v_2)}{5(1-K)} \quad 2.2$$

This expression illustrates the effect of temperature on the extent of swelling. It indicates that if the temperature (T) increases, the absolute extent of swelling (v_2) would be expected to decrease because of the negative sign. The reason for this is that the elastic energy in the polymer network is stored as entropy, not enthalpy. As already mentioned, the energy associated with probabilities of the molecular structure in the polymer chain is called the entropy. When the rubber absorbs the solvent, the chains in the polymer network expand. The chains occupy less probable network configurations and the entropy of the rubber network decreases. Consider the following equation developed by Helmholtz describing the free energy within a solid;

$$\frac{\Delta F}{T} = \frac{\Delta H}{T} - \Delta S \quad 2.3$$

where;

- ΔF = change in free energy
- ΔH = change in enthalpy
- ΔS = change in entropy
- T = absolute temperature

Under isothermal conditions, ΔH is zero because enthalpy is related to the temperature of the solid. If a rubber particle is stretched, free energy is added to the particle as work is done. The entropy will decrease because the $-T\Delta S$ term will have to be positive to facilitate an increase in free energy (ΔF). If the temperature is increased and then maintained so that ΔH will again be zero, obviously T will increase, so the change in free energy i.e the work done in stretching the particle the same amount and achieving an equivalent change in entropy will have to be increased.

When the polymer absorbs the solvent at a higher temperature, the work done in increasing the chain lengths and expanding the network will have to be increased provided the shape of the network is maintained. Therefore, as the mixing entropy of the solvent and the polymer does this work, the equilibrium of swelling will be at a lower volume of swell. Therefore, the maximum volume of swell will decrease with an increase in temperature for a cross-linked polymer such as vulcanised rubber.

However, this is only applicable if there is no change in the constitution of the rubber. Green and Tolonen (1977) found that the maximum amount of swell actually increased through an increase in temperature. This indicates that through the diffusion of bitumen there is another reaction taking place. Green and Tolonen concluded that because the interaction was taking place at temperatures above 155°C, the reversion of the rubber was occurring. When this happens, the cross-link density is reduced and thus the entropy change required to expand the rubber network is reduced. Therefore, the maximum amount of swelling will increase.

The rate of swell is related to the ability of the solvent to diffuse into the rubber. It is commonly agreed that the rate of swell increases through an increase in temperature (Green and Tolonen, 1977 and Takallou and Sainton, 1991). It is also known that the rate of swell is very sensitive to changes in temperature. Oliver (1974) in developing diffusion equations of oils into asphalt found that the diffusion coefficient was related to the activation energy according to Equation 2.4.

$$D = Ae^{-E/RT} \quad 2.4$$

where:

D	=	diffusion coefficient
A	=	constant
E	=	activation energy
R	=	the gas constant
T	=	absolute temperature

Although this is an equation developed for diffusion of oils into asphalt it illustrates that the diffusion process is very sensitive to temperature because T is the denominator of the exponent of the diffusion coefficient.

2.5.3 Effect of Particle Size on Rate of Swell

Crank (1975) developed a relationship for the diffusion in a sphere of a limited volume of solvent and arrived at the following equation;

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=1}^{\infty} \frac{6\alpha(\alpha+1)e^{-R}}{9+9\alpha+q_n^2\alpha^2} \quad 2.5$$

where;

- M_t = mass of solvent in sphere at time = t
 M_∞ = total mass of solvent in sphere at time = ∞
 α = ratio of volume of solvent to volume of sphere
 R = $\frac{Dtq_n^2}{a^2}$
t = time
a = radius of sphere at time = t
D = diffusion coefficient
 q_n = non-zero roots of $\tan q_n = \frac{3q_n}{3+\alpha q_n^2}$

Analysis of this equation shows that, if α remains constant, q_n will remain the same and M_t/M_∞ will remain constant if the ratio of t/a^2 remains constant. Therefore, t is proportional to the radius squared. If the radius is halved, then the time to swell will be reduced by a factor of 4.

2.5.4 Effect of Concentration on the Rate of Swelling

Flory and Rehner (1943, Pt II) developed an expression for the activities of a solvent dissolved in a cross-linked polymer by equating the energies associated with the reaction.

$$\ln a = \left[\frac{Kv_2^2}{2} + \ln(1-v_2) + v_2 \right] + \left[\frac{\rho V_1}{M_c} \right] v_2^{1/3} \quad 2.6$$

where:

- a = activity levels of solvent
 v_2 = volume fraction of polymer
 V_1 = molar volume of solvent
 M_c = molecular weight of the chain
 ρ = density of the polymer

- K = heat of mixing constant = $A + \frac{2BV_1}{RT}$
- A,B = constants dependant on the components
- R = gas constant
- T = absolute temperature

The level of activity can also be classed as the available free energy associated with the swelling reaction. The higher the activity, the greater the initial free energy available to cause the rubber to swell. The initial free energy represents the available work to swell, therefore, the greater the free energy, the greater the maximum amount of swell. This equation is plotted on Figure 2.6 to show how the concentration of polymer is related to the free energy in the system.

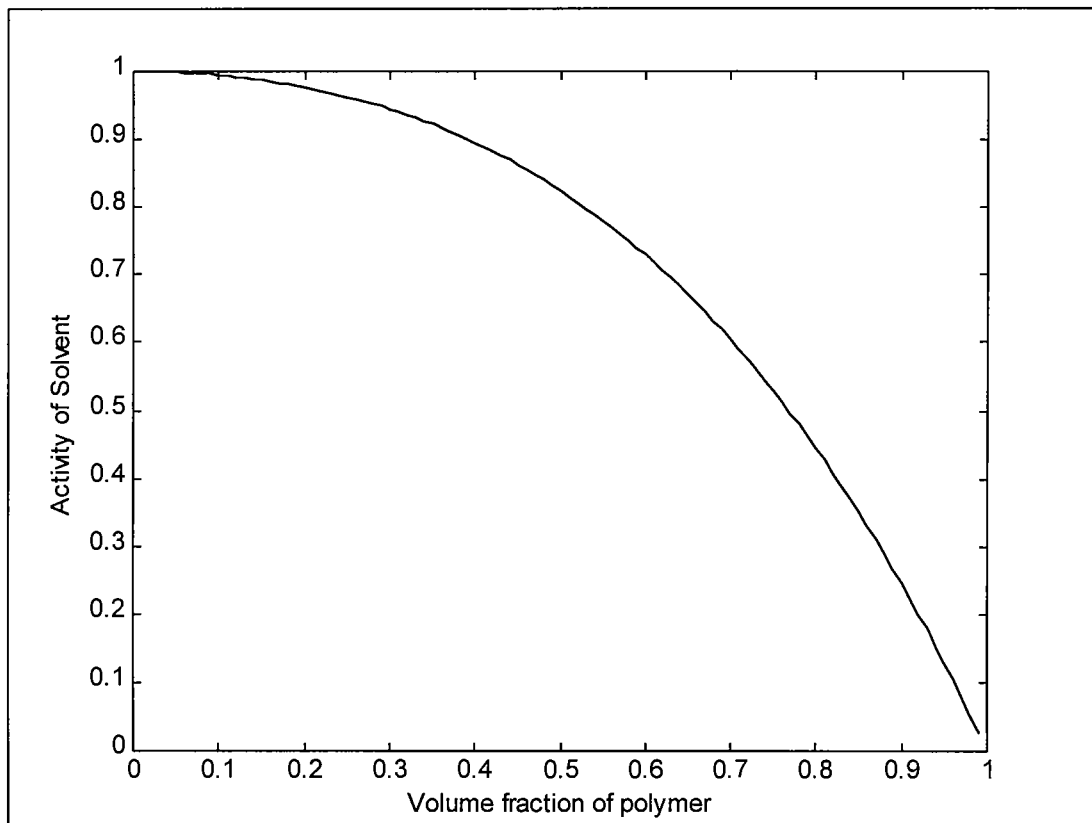


Figure 2.6 - Activities of solvent dissolved in a cross-linked polymer as a function of the volume fraction of the polymer (Flory and Rehner, 1943, Pt II)

Figure 2.6 illustrates that as the volume fraction of the polymer is increased, the activity of the solvent decreases. Therefore, one would expect the maximum amount

of swelling to decrease, with an increase in the polymer fraction or alternatively, a decrease in the concentration of solvent.

2.6 Summary

It has been shown through a review of the literature that when rubber is added to bitumen, the rubber imbibes proportions of the bitumen and swells. The amount of swelling is dependent on the temperature of the reaction, the size of the particles and the concentration of the solvent/bitumen. All these factors need to be accounted for when investigating the swelling reaction between the rubber and the SBS bitumen in IAA. This will facilitate development of a model on the rate of swell in the mixing and laying processes of IAA, so that a design method for a durable material can be produced.

3. EXPERIMENTAL INVESTIGATION INTO BITUMEN-RUBBER INTERACTION

3.1 Introduction

The previous chapter showed that the rubber absorbs some fractions of the bitumen. However, it is not known how this interaction occurs in the IAA mixture and how temperature, concentration of bitumen, the bitumen constitution and the type of rubber affect it. It is also not known what effect this interaction has on the mechanical properties of the bitumen and the IAA mixture. It is suspected that the interaction reduces the amount of available binder and the adhesive/cohesive strength of the residual binder causing the material to fret. An experimental investigation was undertaken to understand the interaction between the rubber and the bitumen in the IAA mixture.

This chapter concentrates on the process of the interaction and outlines the experimental investigation of the parameters that affect the amount and rate of absorption by the rubber. The particular emphasis has been to relate the interaction between the rubber and bitumen to what is happening during mixing, transportation and compaction of IAA, when it is held at an elevated temperature. The effect of temperature was assessed to see how sensitive the interaction was to changes in temperature. The aromatic oil fraction of the bitumen was used to measure the effect of temperature so that a relationship could be related to Equation 2.2. This was because it was sufficiently fluid at low temperatures to be drained from the samples of rubber. This work also gave an indication of the variability of rubber within the rubber crumb and an indication of the rate of interaction after construction. The interaction between the rubber and the SBS PmB was assessed by measuring the amount of bitumen the rubber absorbed by curing samples of rubber in bitumen at different concentrations. This work produced swelling curves based on SBS PmB that can be used to give an indication of the rate of interaction taking place in the IAA during mixing, transportation and compaction (i.e. at elevated temperatures). The following chapter concentrates on the effect the interaction has on the mechanical performance of the bitumen and the rubber.

3.2 Swelling Tests

The construction of IAA is a batch mixing process where crumb rubber is added to hot aggregate, mixed dry and then mixed with hot SBS PmB. It is important to maintain the material at mixing temperature (155°C) during the transportation period so the bitumen is fluid and the material is workable and can therefore be compacted sufficiently. The transportation period can be up to 6 hours depending on the distance between the batching plant and site. The initial in-situ trials suggested that the length of time the material is held at mixing temperature is affecting the mechanical durability of the material. Essentially, the longer the material is held at high temperatures, the poorer the mechanical durability of the end product, suggesting that the interaction between the rubber and the bitumen is at its peak during this period. However, it is also possible that the interaction is taking place in service. To investigate this, testing was carried out at a range of temperatures using the flux oil component of the SBS PmB.

3.2.1 Swelling of Rubber in Flux Oil

The initial task was to investigate the effect of temperature on the rate of swelling. Using SBS PmB at different temperatures is difficult because it is viscous at low temperatures and therefore, would influence the film thickness surrounding the rubber. It would also affect the way in which it flowed and diffused into rubber particles. As indicated by Heitzman (1991), the main fraction of bitumen that is absorbed by the rubber is the aromatics. Flux oil, containing the aromatic fraction of SBS PmB was therefore used to investigate how the rate of reaction is affected by temperature because it is fluid at room temperature and stable at temperatures up to and above 200°C.

Method

The effect of temperature on the rate and magnitude of swelling of vulcanised crumb rubber was tested by preparing a number of rubber samples of similar shape and size and placing them in separate containers of flux oil. The rubber samples were periodically removed from the flux oil, dabbed to remove excess oil, weighed and

then placed back in the same flux oil to enable the diffusion process to continue. Volumetric measurements were found to be difficult because the test has to be halted when taking measurements. In addition, Green and Tolonen (1977) found when carrying out similar tests, measuring the increase in mass was more accurate than measuring the increase in volume. The advantage of measuring the mass is that it directly relates to the amount of bitumen/oil absorbed by the rubber.

Figure 3.1 shows a schematic of the general apparatus. For temperatures below 80°C the beakers were placed in a water bath as this provides accurate control of the temperature of the oil. For temperatures above 80°C the beakers were placed in the oven and care was taken to monitor the temperature of the oil to ensure the accuracy was not affected.

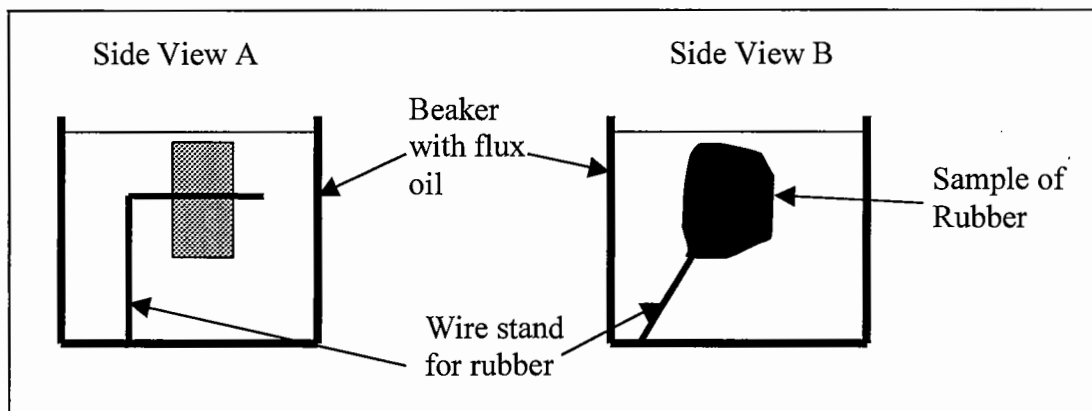


Figure 3.1 - Beaker apparatus for rubber swelling experiments

The rubber samples were prepared from larger pieces of recycled rubber crumb extracted from the early stages of the Crackermill process. The larger pieces were used because they could be handled separately and are therefore easier to weigh. The pieces were cut into shape so that each piece had approximately a 20mm external diameter that weighed between 2-3g and were in a uniform shape allowing the surface area to be estimated. Two samples were prepared from the same piece so that a comparison could be made between the variability of the types of rubber in the crumb. Each sample was then skewered by a wire frame to hold the sample in the flux oil without touching the sides of the jar. This meant that the whole surface of each sample was in contact with the oil.

Six beakers were prepared by placing flux oil 8 times the mass of the rubber particle into each container. The oil was then placed in the water bath or oven for 1 hour to condition for temperature. One sample was placed into each beaker that was then covered and placed into the water bath or oven. Initially, samples were removed every hour, shaken, dabbed free of excess oil and then weighed. The amount of excess oil removed was negligible compared to the mass of the rubber samples so this process was not deemed critical but was repeated for each experiment to provide continuity as some oil collected on the wire frame. The samples were then placed back in the oil and allowed to continue to absorb the oil. The same amount of oil was used, so as the rubber absorbed the oil, the amount of available oil decreased because no more was added, so the concentration of rubber to oil/bitumen that is quoted, represents the initial conditions. The weighing periods changed depending on the rate of increase so that a smooth curve could be formed from the data. The temperatures used for investigating rubber swelling in flux oil were; 40, 77, 132 and 170°C.

Results

To see the effect of the rubber type on the swelling experiments, two samples were taken from each of three pieces of crumb from a batch that are not necessarily the same type. This provided an indication of the variability of results due to different types of rubber in the crumb batch. Figure 3.2 shows a graph taken from measurements of the increase in mass for samples soaked in flux oil at 40°C.

The amount of swelling for each sample is shown in Figure 3.2 and it shows that the swelling rates are varied for each piece of rubber. The two samples taken from piece no. 3 (Samples 3A and 3B) swell about half as much as the other samples. This indicates that there is considerable variation within the crumb rubber for swelling in the oil and suggests that a test sample of three different pieces of rubber is not sufficient to describe the rate of swell for a batch of crumbed rubber. Further testing was carried out to measure the repeatability of the test. Figure 3.3 shows the mass increase at different temperatures averaged for the six samples. The error bars represent 95% confidence limits for the results based on the repeatability study on 20 samples and calculated assuming a Gaussian (Normal) probability distribution. These results are based on the mass increase for individual samples. Although the samples

were prepared in a similar way, they were not exactly the same shape and size. Therefore the results have been normalised by using the estimated surface area to work out the effective film thickness of flux oil on each sample based on the mass of flux oil they absorbed. This assumes that there is no absorption of the flux oil by the rubber, which is incorrect, but this is a simple way of normalising the results for the different sizes of rubber. The surface area was estimated by measuring the external dimensions of each sample assuming a rectangular solid. These results are shown on Figure 3.4.

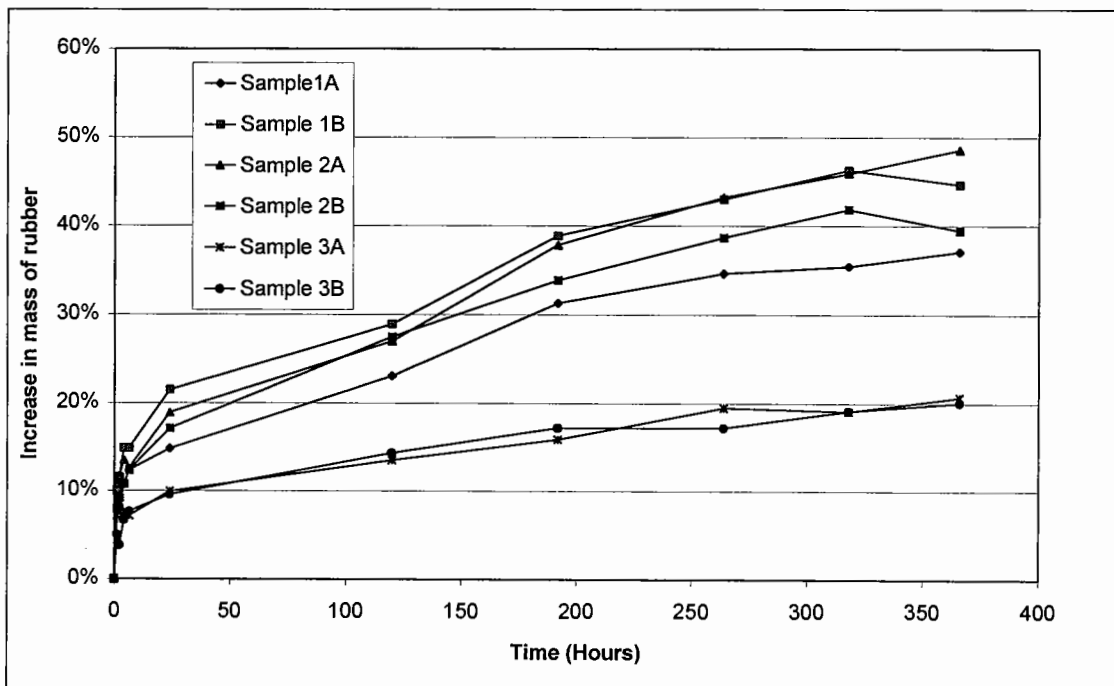


Figure 3.2 - Increase in mass of samples of rubber soaked in flux oil at 40°C

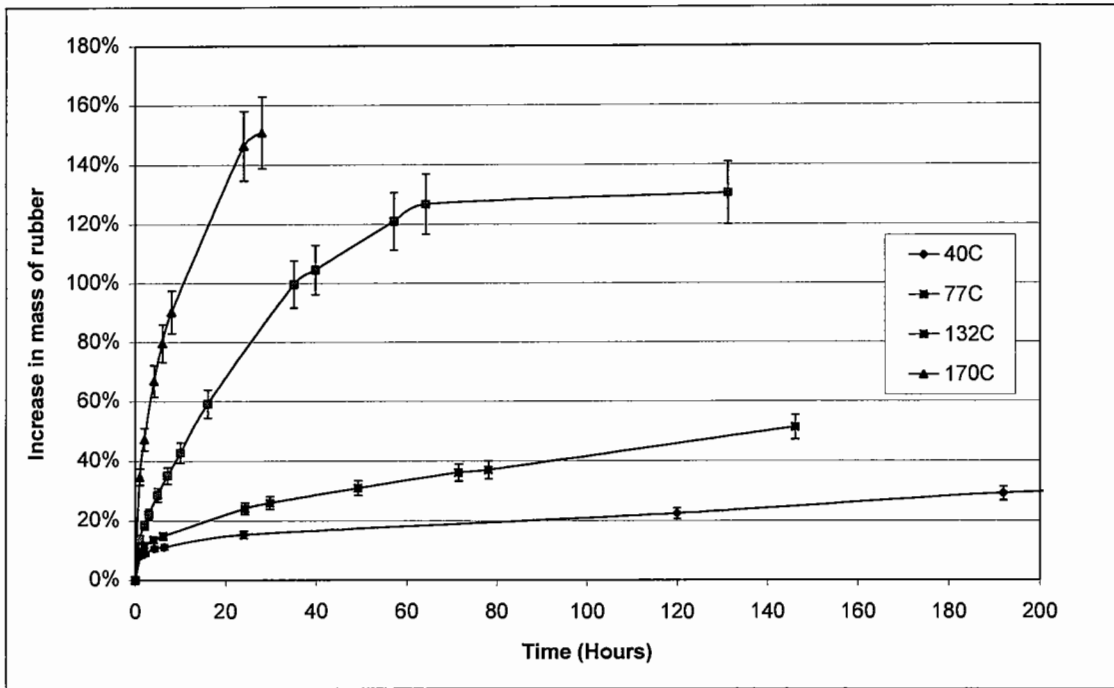


Figure 3.3 - Mass change of samples of rubber soaked in flux oil at different temperatures

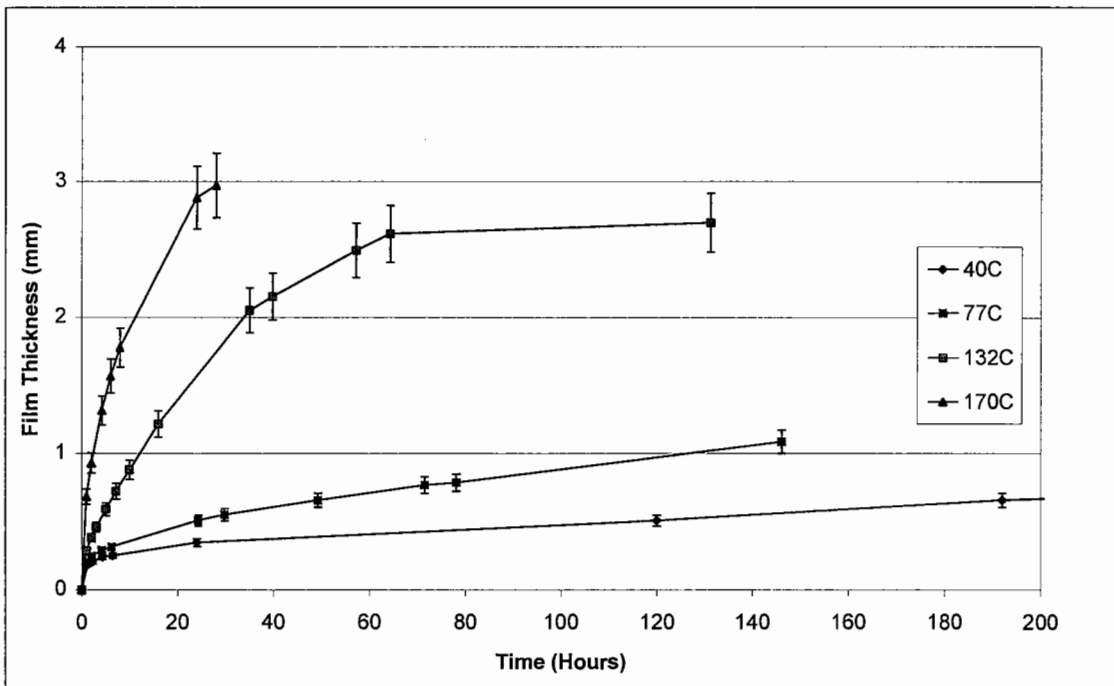


Figure 3.4 - Estimated film thickness of flux oil on rubber after soaking at different temperatures

Discussion

The results show that there are two effects that accompany an increase in temperature. Firstly, the rate of swelling increases and secondly, opposite to what should happen in theory outlined in Section 2.4, the maximum amount of swelling increases. Green and Tolonen (1977) developed the following equation for swelling of rubber in oils based on a ratio of maximum swell;

$$s = s_m(1 - Ce^{-kt}) \quad 3.1$$

where;

s	=	percent swell by mass
s_m	=	maximum swell possible at time, $t = \infty$
k	=	rate of swell (1/hr)
C	=	constant
t	=	time (hr)

For convenience of plotting, Equation 3.1 was rearranged as follows;

$$\ln\left(\frac{s_m}{s_m - s}\right) = kt - \ln C \quad 3.2$$

It can now be seen that if $\ln(s_m/s_m-s)$ is plotted against t the result is a straight line of gradient k. The maximum swell value (s_m) was adjusted until a straight line that fitted the data was obtained. Figure 3.5 illustrates these lines and Table 3.1 gives the values of the constants, swelling rates and maximum swell for the rubber in flux oil at different temperatures.

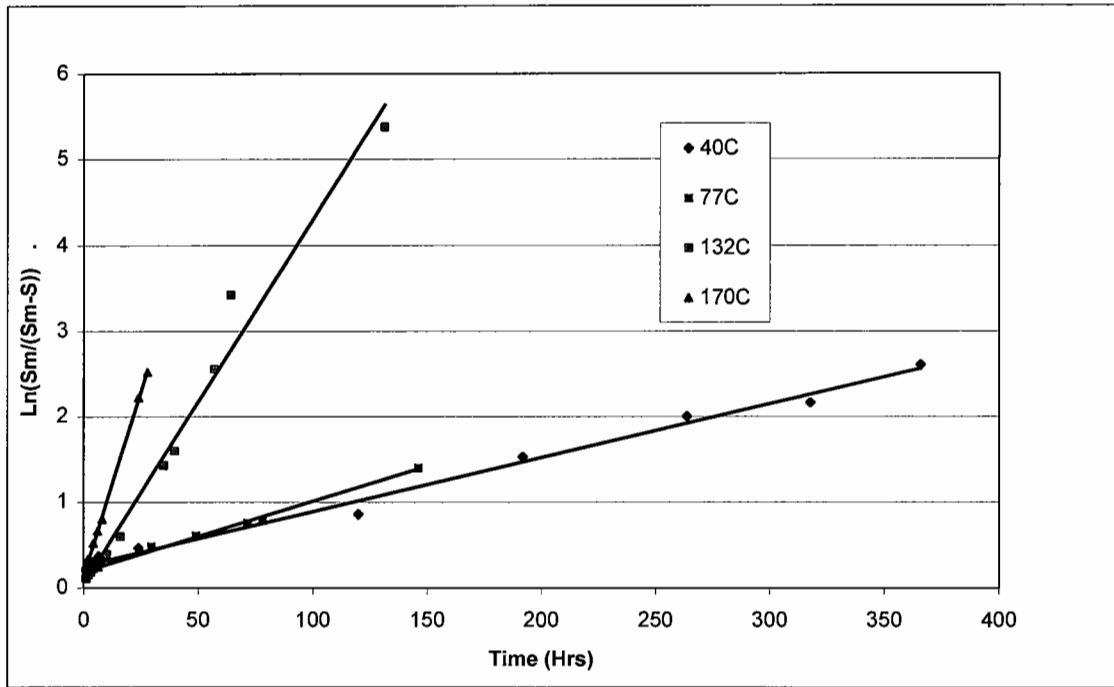


Figure 3.5 - Relationship between maximum swell for rubber and curing time for flux oil at different temperatures

Table 3.1 - Summary of rate equation constants for swelling of rubber in flux oil

Flux oil Temperature	S_m - maximum amount of swell	k- rate of swell (hr^{-1})	C - constant
40°C	40%	0.0063	0.773
77°C	68%	0.0082	0.827
132°C	131%	0.0425	0.952
170°C	164%	0.0852	0.856

The values of the rate equation constants fitted to the measured data illustrate that the maximum swelling increases almost proportionally with temperature and the rate of swelling increases but at a rate faster than the increase in temperature. Figure 3.6 illustrates that the relationship between the rate of swelling and temperature is almost exponential, which agrees in part with the theory set out by Oliver (1974) described in Section 2.5.2. However, only a limited number of tests have been carried out, so if this relationship is going to be of use, swelling experiments should be carried out over a greater range of temperatures.

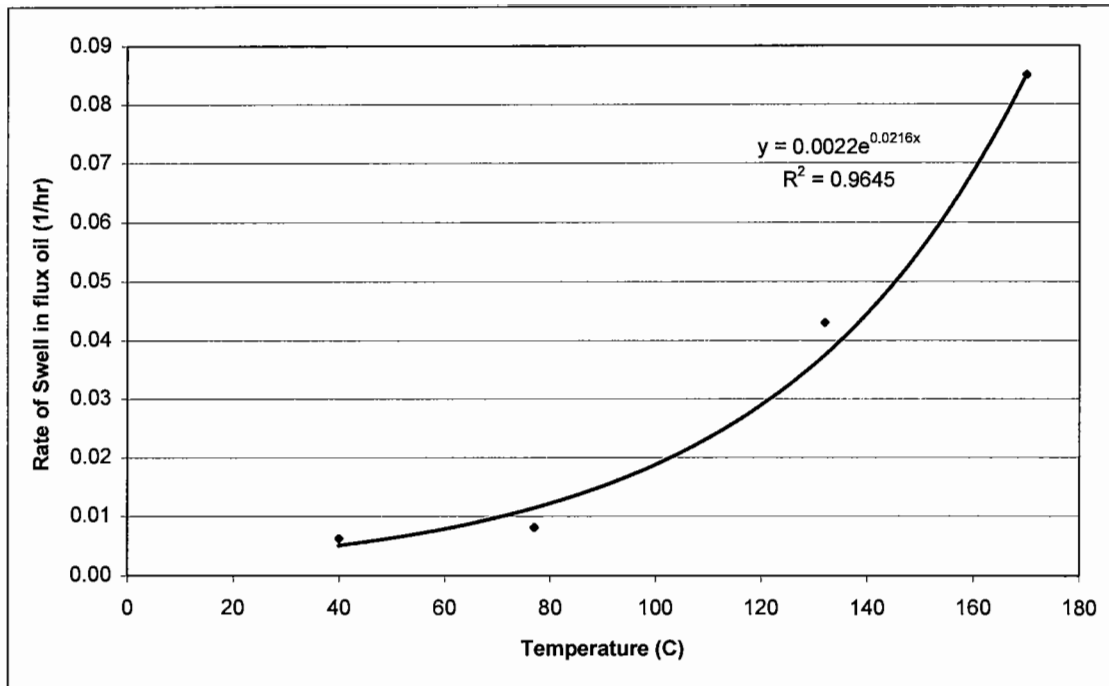


Figure 3.6 - Relationship between rate of swell and temperature for rubber cured in flux oil

Summary

Preliminary tests carried out on 20mm samples of crumb rubber have confirmed a number of points mentioned in the literature review and also raised some limitations associated with the accuracy of the tests. It has been shown that rubber from the crumbing of truck tyres swells when placed in flux oil. The rate of swelling increases with an increase in temperature, but the maximum swelling also increases. This is contradictory to the theory, where equating entropies led to the conclusion that an increase in temperature of vulcanised rubber would reduce the ability of the rubber to absorb the oil. This may indicate that the chemical structure of the vulcanised rubber is changing due to either the absorption of oil and/or the exposure to high temperature. It is also noticeable that the rubber is reacting with the flux oil at low temperatures. This may indicate that the reaction between the rubber and the bitumen can continue, although at a lower rate, when the material is in service. However, the high viscosity of the bitumen at ambient temperatures may reduce the interaction significantly, this is an area that needs further consideration and is not considered in this project.

Monitoring the rate of swelling for individual samples has shown the high degree of variability because of the different types of rubber in the crumbed batch. Therefore, tests have to be carried out with a greater sample batch to be more simulative to generate more accurate rate equations.

The next stage is to compare the swelling in flux oil with swelling in bitumen. It is known that the SBS PmB contains around a proportion of flux oil added to a low asphaltene content bitumen and SBS polymer. The following section describes the development of a test method to measure the mass increase of smaller particles of rubber. This would aid in developing a relationship between the size of rubber particles and the rate equations.

3.2.2 Swelling Experiments in Bitumen

The mechanism of swelling requires the solvent to be fluid to allow it to diffuse into the rubber. Bitumen at room temperature is a 'solid' fluid making diffusion into the rubber slow and difficult to measure. Therefore, the bitumen must be raised in temperature to make it fluid enough to diffuse into the rubber and drain off to allow repeatable measurements. A temperature of 155°C was chosen because this is the temperature the mixture is held at when mixing, transporting and compacting in the production of IAA. This is of particular relevance to this project as it is felt that when the material is being mixed and laid i.e. when it is at hot temperatures, the interaction between the rubber and the bitumen is critical.

Method

To compare with results from the oil swelling tests the same test procedure was used. Six samples between 2-3g in weight were prepared from six different pieces of crumb, so that the surface area could be estimated and the size and shapes were similar. The SBS PmB was heated up to 185°C for 1 hour and then eight times the mass of the rubber sample was placed in the containers. The rubber samples held at ambient temperature were added to the containers which had cooled slightly to about 155°C, as in Figure 3.1, and then placed in the oven at 155°C. Periodically each of the samples was removed, shaken and then weighed. Due to the highly adhesive nature of the

bitumen, dabbing the sample free of excess bitumen was impossible without affecting the sample. Therefore, the sample was shaken free of excess bitumen and then weighed. Although this meant that there was more bitumen on the sample than would be the case in a mixture, the rate of increase would still be the same because the method of measurement was kept consistent.

The next step was to use smaller crumbed rubber samples to investigate the effect of particle size on the rate of swell. Two different gradings of crumb rubber particle were selected because they are used for IAA; 1-4mm and 6-9mm. These gradings are collected from the Crackermill Process where the tyres are sequentially ground into smaller pieces and sieved to produce graded batches of crumb rubber with the cord and wire removed. Five grams of each crumb rubber grading were placed in 60ml containers. This provided a good variation of types of rubber and gives a more repeatable result. The crumbed rubber particles were placed in the containers with 40g of hot SBS PmB. Each beaker was then placed in the oven for a set time, removed and the contents poured on to a sieving grid and placed back in the oven for a further hour. The grid was of suitable size so that the excess bitumen would drain through into another receptacle and the rubber particles would stay on the grid. The extra hour in the oven for drainage was used to make sure that the bitumen was at the same temperature and therefore a similar viscosity when draining.

The residual bitumen was collected so that mechanical and chemical analysis could be carried out and compared to bitumen cured under the same conditions but without rubber. The details of this are given in the following chapter.

Results

The 20mm samples of rubber were soaked in bitumen for 52 hours at 155°C. The mass increase was monitored periodically and the results are presented in Figure 3.7 for each of the samples. The sixth sample came off the wire frame and could not be handled, so the data was lost. The test had to be halted because the rubber samples were beginning to disintegrate in the bitumen after 52 hours. The crumb rubber particles (1-4mm and 6-9mm) were soaked in bitumen for different times, removed, drained and then weighed. The results for the mass increase over time are given in

Figure 3.8. The error bars represent 95% confidence limits based on a Gaussian (normal) distribution gathered from a repeatability study of 10 samples at a 6 hour curing period.

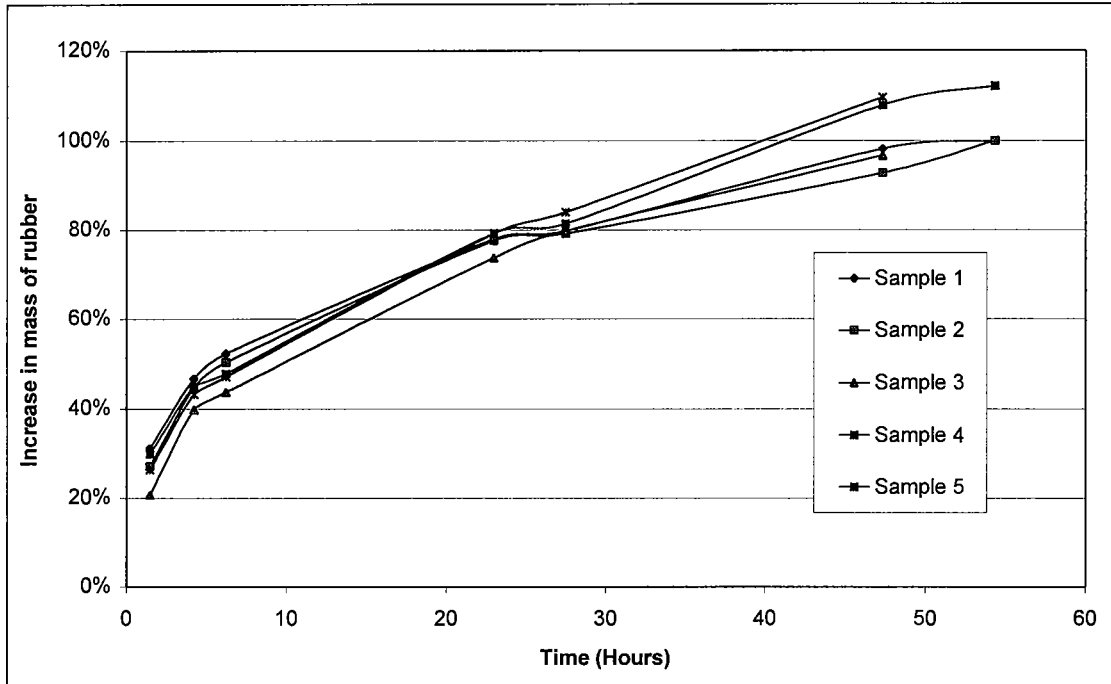


Figure 3.7 - Mass increase of 20mm samples of rubber cured in SBS PmB at 155°C

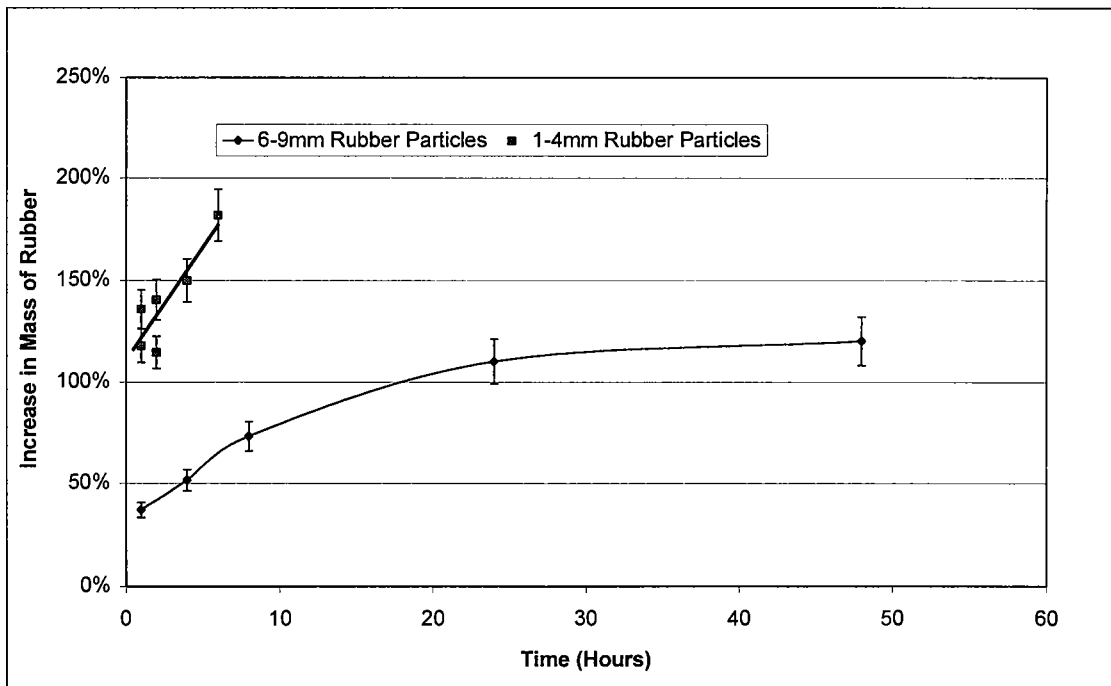


Figure 3.8 - Mass increase of different gradings of rubber crumb particles in SBS PmB at 155°C

The results from the different crumb rubber sizes along the data collected from the 20mm particles have been fitted to Equation 3.1 and are presented in Figure 3.9 to illustrate the effect of particle size on the rate and amount of swelling. The maximum swell, rate of swell and constant are summarised in Table 3.2.

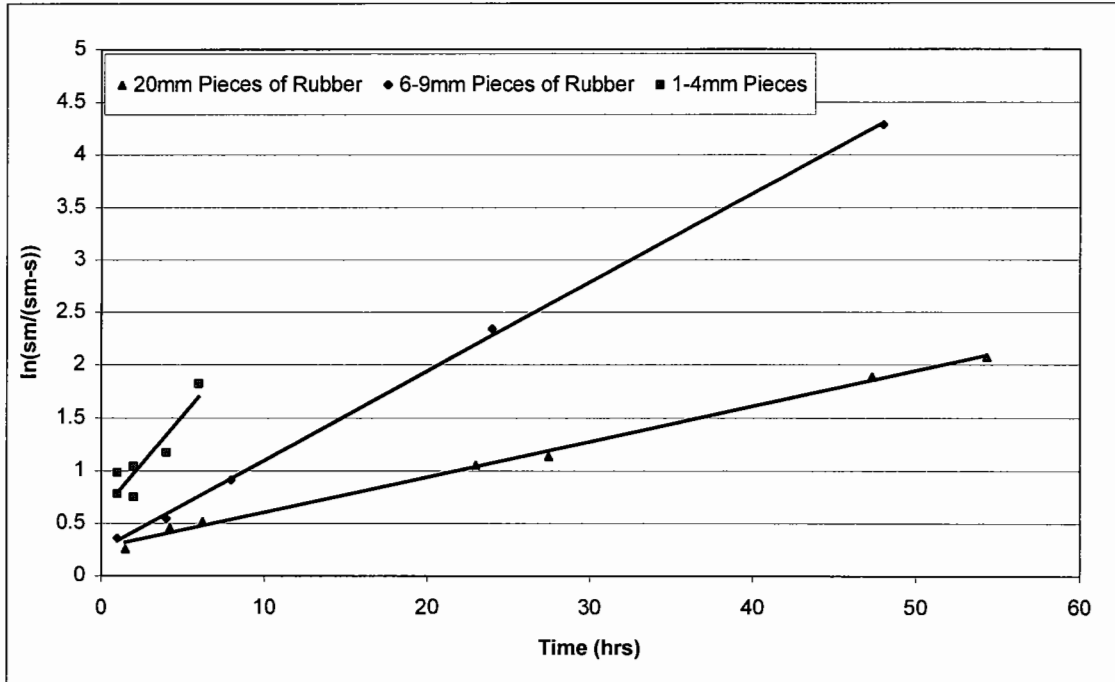


Figure 3.9 - Relationship between the crumb rubber particle size and the rate of swelling

Table 3.2 - Summary of rate equation constants for swelling of rubber in SBS PmB

Rubber Type	S_m - maximum amount of swell	k- rate of swell (hr^{-1})	C - constant
20mm samples	119%	0.0334	0.776
6-9mm crumb	122%	0.0845	0.759
1-4mm crumb	217%	0.1865	0.590

Discussion

It should be noted that a direct comparison of these results to the results from the swelling experiments carried out in the flux oil is not possible because they were carried out at different temperatures. However, the 20mm samples tested in bitumen at 155°C had a lower maximum amount of swelling and rate of swelling than the

20mm samples tested in flux oil at 132°C. This indicates that the flux oil is more reactive with the rubber than the bitumen. It is difficult to assess exactly what is reacting with the rubber from the SBS PmB because, although it is probably the flux oil, there will be other fractions from the low asphaltene content bitumen in the blend that are able to react with the rubber. Therefore, although the concentration of the flux oil in the bitumen is known, it is not possible to assume that this represents the concentration of reactive solvent in the bitumen.

The preliminary tests investigating the effect of particle size of rubber show that a smaller particle size has a faster rate of swelling. This is expected because a smaller particle size represents a larger available surface area for the same mass of rubber for the bitumen to react with. However, the literature review presented a relationship developed by Crank (1975) that stated that the time to swell or the reciprocal of the swelling rate is proportional to the radius squared. Therefore, if the radius is halved the swelling rate should increase by a factor of 4. However, the comparison of rate of swelling between the 1-4mm, the 6-9mm and the 20mm particles does not follow the same relationship as can be seen in Table 3.3. The table shows that the 20mm particles have a larger radius, on average, than the 6-9mm particles by a factor of 2.5. If the relationship developed by Crank (1975) is to be proven, the increase in rate of reaction from the 20mm particles to the 6-9mm particles should be by the square of 2.5, which is 6.25 times. However, the results show that the increase is only 2.53 times. The relationship between the radii and the swelling rate is similar between the 1-4mm and 6-9mm particles, confirming that the swelling rate for the rubber crumb is not proportional to the reciprocal of the radii squared. It is actually closer to being proportional to the reciprocal of the radius. This indicates that the interaction is happening throughout the particle and not just on the surface where the rate would be affected solely by the surface area.

Table 3.3 - Summary of the ratio of swelling rate and radius

	Average radius	Ratio	Rate of Swell	Ratio
20mm Particles	20mm		0.0334	
6-9mm Particles	7.5mm	$20/7.5 = 2.5$	0.0845	$0.0845/0.0334 = 2.53$
1-4mm Particles	2.5mm	$7.5/2.5 = 3$	0.1865	$0.1865/0.0845 = 2.21$

It is also noticeable that the maximum amount of swelling estimated with Equation 3.1 is similar for the two sets of larger particle sizes, but not for the 1-4mm particles. This is thought to be due to the bitumen not draining through the 1-4mm particles as easily. The smaller size particle grading was able to retain more bitumen through having smaller voids between each particle. Therefore, the maximum swelling is misleading as it actually represents the amount of bitumen retained in the batch which is the amount that the rubber has absorbed and the amount that is held within the voids. However, the rate of swelling is comparable because the amount retained in the voids will be similar for each measurement, so the increase in bitumen retained can be assumed to be the bitumen that is absorbed by the rubber. The maximum swelling of the larger two gradings are comparable because the excess bitumen was able to drain off the particles. This would suggest that the maximum amount of swell is independent of the surface area and therefore the solvent is reacting with all of the rubber and not just the outer layer of the particle.

Summary

Swelling tests in bitumen have shown that the rubber will swell when placed in a high concentration of bitumen at high temperatures. It has also been shown that the rate of swelling and the maximum amount of swell are lower for the bitumen than the flux oil, suggesting that the flux oil is a more reactive solvent. The particle size of the rubber has also shown to have an influence on the rate of swelling but not on the maximum amount of swelling.

The intention of this work is to develop a physical model of the interaction that occurs in the IAA. The effect of particle size in large concentrations of bitumen has been addressed, it is now necessary to alter the concentration of the bitumen to rubber to investigate what happens at the lower concentrations of bitumen that occur in the mixture.

3.2.3 Effect of Concentration

A bitumen concentration of 8 times the mass of the rubber was chosen for the preliminary testing because that was the amount of bitumen required to completely cover the rubber particle in the method using 20mm particles. However, this concentration and particle size is not realistic for reproducing the interaction in the IAA mixture. It has already been found that a batch of crumb rubber is needed to account for the variability of the rubber samples. The initial work with the swelling in bitumen showed that the curing and draining of crumb rubber was easiest using the 6-9mm particles as they drain the excess bitumen well and were easier to handle. Therefore, as a standard curing test to assess the interaction between the rubber and the bitumen, batches of 6-9mm rubber are soaked in bitumen for different periods, drained on a grid and then weighed. This method was used to measure the effect of the bitumen concentration on the rate and amount of rubber swelling.

The initial aim of investigating the interaction between the rubber and the bitumen was to characterise what was happening in the IAA mixture. The basic mixture proportions of IAA are 10% SBS PmB, 15% rubber and 75% aggregate by mass. It is difficult from this information alone to derive the amount of bitumen available to interact with rubber when in the mixture. The largest proportion of bitumen available for the rubber would be if the bitumen did not coat any of the aggregate. Although this is unrealistic, it suggests that the ratio of rubber to rubber-bitumen is a minimum 60% ($15/(10+15)$). In previous swelling tests the proportion of rubber to the rubber-bitumen mixture has been a lot less ($1/(1+8) = 11\%$). Therefore, to be able to estimate the rate and magnitude of the interaction in the mixture, higher concentrations of rubber must be cured in SBS PmB. The aim is to find the maximum amount of bitumen that can be absorbed by the rubber and to find how changing the

concentration of rubber affects the rate of reaction to give a better understanding of the factors that affect the interaction.

Method

The aim was to cure a number of different concentrations of rubber-bitumen to develop a relationship between the rate of interaction and magnitude of swelling with the concentration of rubber. The relationship developed can estimate the interaction rate and magnitude for the high concentration of rubber to bitumen in the mixture.

The samples of crumb rubber were weighed into 5g batches and each batch was placed in a 60ml glass jar. A quantity of SBS PmB was heated to 185°C in an oven and conditioned at that temperature for 1 hour. The container of bitumen was then removed from the oven and the hot, liquid bitumen was poured into the jars containing the rubber. The jars were lightly shaken to ensure that all the rubber was in contact with the bitumen. The mass of bitumen added was measured to give a predetermined rubber to rubber-bitumen concentration. The chosen concentrations were 11% (40g of bitumen), 14% (30g of bitumen), 20% (20g of bitumen), 33% (10g of bitumen), 40% (7.5g of bitumen) and 50% (5g of bitumen). During the test it was ensured that there was no surface of rubber unable to interact with the bitumen by covering the rubber particles. Therefore, to ensure all of the particles were covered with bitumen the maximum concentration was 50% rubber. The jars containing the rubber and bitumen were then placed in a force draft oven set at 155°C. Each concentration had 7 jars, from which one jar from each concentration was removed from the oven at time intervals 1, 2, 4, 6, 24, 48 and 72 hours. When each jar was removed, it was turned upside down over a 2mm mesh to drain the residual bitumen into a separate jar. The jars and grid were then placed back in the oven for a further hour to allow the excess bitumen to drain through completely. The rubber was then removed from the grid and weighed using accurate scales. The increase in the mass of the rubber was calculated.

Results

The recorded data from the concentration tests are presented in Figure 3.10, showing the increase in mass of rubber against time. These results show that the concentration of rubber to bitumen is altering the magnitude of swelling in the rubber. However, for the first 6 hours of curing the rate of swelling does not appear to be significantly altered by changing the concentration of the rubber. The magnitude of swelling appears to be controlled by two factors. The first is that under these conditions (155°C and 6-9mm crumb rubber) the maximum amount of swelling of the rubber, if sufficient bitumen is available, is an increase in mass to around 110%. This is illustrated by the swelling curves for 11%, 14% and 20% rubber and can be deemed equilibrium swelling at 155°C for the rubber where the bitumen has soaked into the rubber sufficiently to give an equal concentration throughout the rubber particles. However, as the amount of bitumen is reduced the maximum amount of swelling is also reduced. This second factor is better illustrated by showing the same results in terms of the amount of available bitumen that has been absorbed as shown in Figure 3.11.

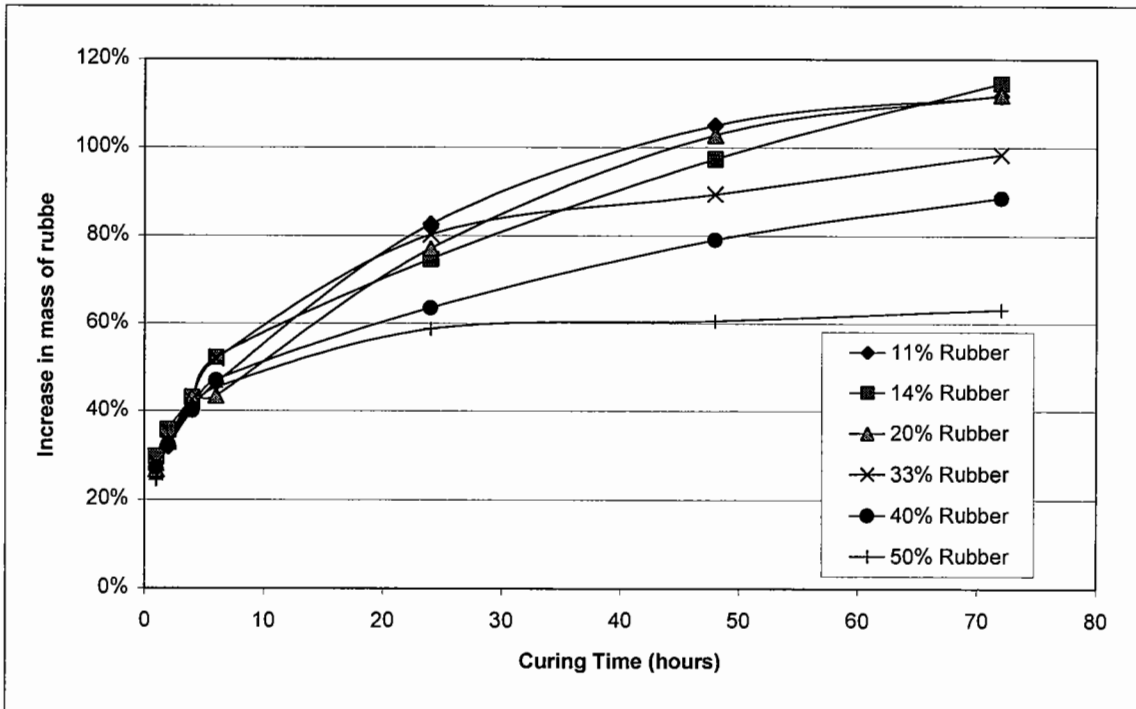


Figure 3.10 - Swelling curves for different concentrations of 6-9mm crumb rubber cured in SBS PmB at 155°C

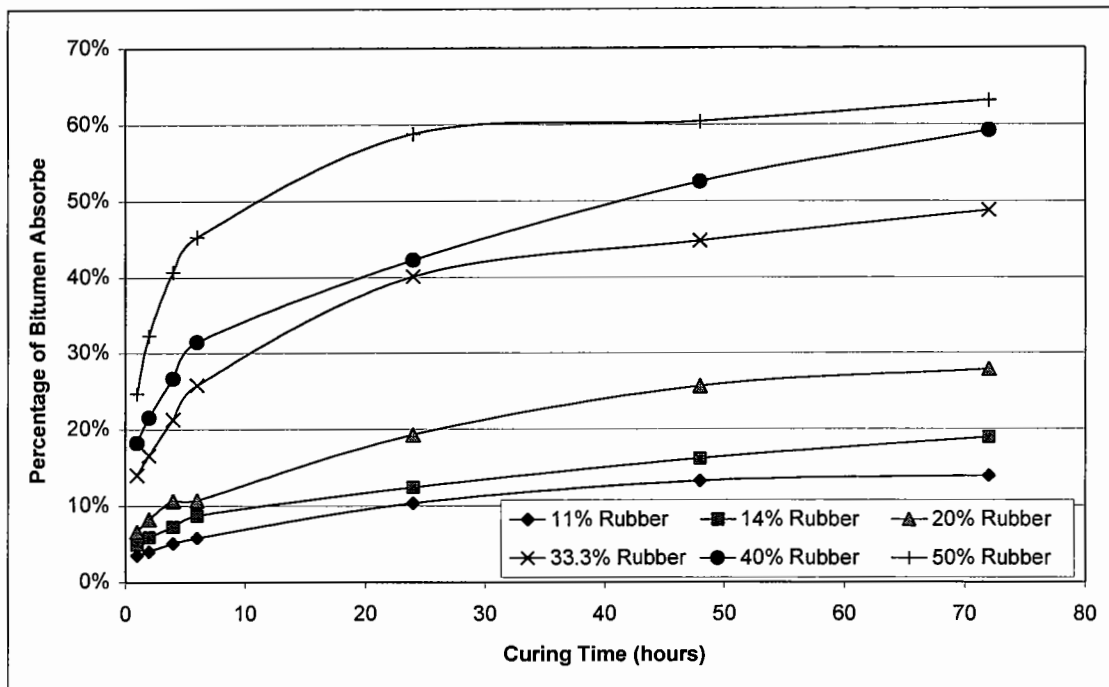


Figure 3.11 - Swelling curves showing the percentage of available bitumen absorbed by 6-9mm crumb rubber at 155°C

This figure shows that for the two highest concentrations of rubber (40 and 50%) the maximum amount of bitumen that can be absorbed is approximately 60% by mass. Therefore, the magnitude of swelling in the IAA mixture is likely to be controlled by the proportion of available bitumen. Of this amount of bitumen available, the rubber will absorb only 60% of it at 155°C. The remaining 40% proportion of the bitumen that is not absorbed by the rubber is likely to be the SBS polymer and the higher molecular weight compounds, such as the remaining asphaltenes. Therefore, if the amount of bitumen in contact with the rubber in the IAA mixture is known, the maximum amount the rubber can swell in the mixture can be estimated.

Discussion

Another factor concerning the change in concentration is the rate of swelling. As already noted, the rate of reaction for the first 6 hours of swelling appears to be approximately constant regardless of the concentration of rubber. Figure 3.12 shows this region in more detail.

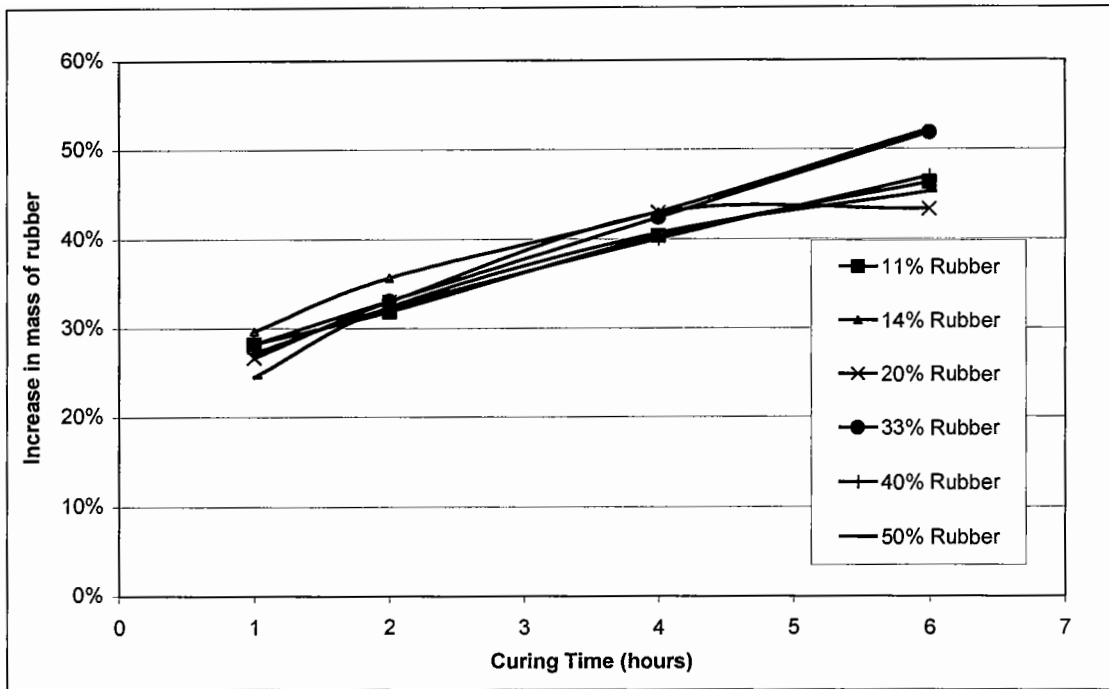


Figure 3.12 - Swelling curve from 1-6 hours for different concentrations of 6-9mm diameter crumb rubber in SBS PmB

It should be noted that none of the concentrations have absorbed 60% of the available bitumen for up to 6 hours. Therefore, the rubber will absorb bitumen in the mixture at this rate until the remaining bitumen in contact cannot be absorbed. This gives an indication of the speed of the interaction and how important the transportation period is for the material.

The work so far has been limited to the interaction between the rubber and the bitumen. The intention was to gain some indication on the process within the IAA mixture when it is being mixed and transported. As already mentioned, the typical mixture contains 10% bitumen, 15% rubber and 75% aggregate by mass. The surface area of the aggregate can be estimated by assuming spheres with the aggregate grading as the maximum diameter. The amount of bitumen on the aggregate can then be estimated by assuming an average film thickness of around 5 microns; a typical film thickness on an aggregate particle for an SBS PmB, (Scholz, 1995) then simply multiplying by the surface area of the aggregate to find the volume of bitumen. The estimated volume of bitumen can then be multiplied by its density to give an estimate of the mass of bitumen on the aggregate. If it is assumed that the remainder of the total bitumen is available to absorb into the rubber, then the concentration of rubber to aggregate can be estimated. In a conventional slab made in the laboratory this would

equate to 250g of the original 350g being available to 500g of 1-4mm rubber particles. This relates to a rubber concentration of 67%. If the above relationship developed for the amount of bitumen that can be absorbed applies, then the 60% of the 250g of bitumen can diffuse into the rubber, which equates to a mass of 150g. Therefore, the rubber can increase in mass from 500g to 650g, an increase of 30%. Referring to Figure 3.12, the time it would take for the rubber to increase in mass by 30% is 1.5 hours. However, this refers to 6-9mm rubber particles and the typical mix investigated here uses 1-4mm particles. It was established earlier that the rate of reaction for 1-4mm particles was about 2.5 times quicker than that for 6-9mm particles. This would infer that the reaction between the rubber and the available bitumen would be over in just over 30 minutes.

This figure appears small and there are a number of factors not taken into account that could slow the interaction down. Firstly, the theory above assumes that all the bitumen that is not coating the aggregate is available to be absorbed into the rubber. Although this may be the case, the actual position of the bitumen in relation to the rubber in the mixture matrix may make it difficult for some of the bitumen to reach a particle of rubber, i.e. trapped in a void between aggregate particles. Therefore, the interaction will be slowed because the bitumen is not able to reach the rubber particles. The surface area of the rubber in the IAA mixture will also be reduced because of contact with other particles. Also, the curing experiments use the bitumen in its pure form. When it is mixed with the aggregate and the rubber, the fine aggregate particles known as the filler, mix with the bitumen and form a bitumen-filler mastic that has a higher viscosity and will reduce the ability of the bitumen to diffuse into the rubber. Therefore, the interaction between the rubber and the bitumen will be slowed through the inability of the bitumen to reach the rubber particles. The most effective method of looking at how quickly the interaction occurs in the material is to carry it out in the material and investigate the effect on the material. This will be looked at in Chapter 5 and 6 when investigating the change in mechanical durability of the material through curing.

Summary

The process of the rubber absorbing the bitumen and swelling has been illustrated through some simple curing tests. It has been shown that the amount of absorption is dependent on the temperature, the particle size of the rubber and the concentration of the rubber. A simple model has been generated to investigate the rate of interaction in the material. It appears that the rate is likely to be controlled by the matrix of the material and will be investigated by looking at the change in material properties through curing.

It has been suggested that it is the lighter molecular weight fractions of the bitumen that are being absorbed by the rubber, thus leaving the residual bitumen with a large proportion of the heavy fraction. If this is the case, the performance of the residual bitumen will differ from that of the original before it has reacted with the rubber. To investigate this, mechanical testing on the residual bitumen was carried out and is described in the next chapter.

4. MECHANICAL TESTING ON RESIDUAL BITUMEN

4.1 Introduction

The swelling tests provided proof that the rubber will absorb the SBS PmB at mixing, transportation and compaction temperatures of the IAA mixture. If this is occurring, then the simple solution is to add more bitumen to accommodate the loss to the rubber. However, evidence from the literature outlined in Chapter 2 indicated that the lighter molecular weight fractions of the bitumen will more readily be absorbed by the rubber. If this is occurring in the curing tests, it is likely that the colloidal structure of the residual bitumen will also be altered suggesting that the mechanical properties of bitumen in the IAA mixture are changing through the interaction. This could have an effect on the ability of the bitumen to bind the aggregate and rubber together. Therefore, adding more bitumen may not be sufficient to accommodate the interaction between the rubber and the bitumen. The mechanical properties of the residual bitumen from the curing tests were measured to give an indication of how the SBS PmB in the IAA is altered due to the interaction between the rubber and the bitumen.

The Dynamic Shear Rheometer (DSR) was used to measure the changes in the rheological properties of residual bitumen that was allowed to cure in rubber and compare them with those cured without rubber under the same conditions. The difference in properties would be attributable to the interaction between the rubber and the bitumen. The Vialit Cohesion Test is a test designed to measure the cohesive characteristics of the bitumen. It was used on the rubber and air cured samples of bitumen to measure any changes in cohesion of the bitumen due to the interaction between the rubber and the bitumen. The effect on the mechanical performance of the rubber was also assessed to establish what was happening to the rubber in the IAA mixture through the interaction with the bitumen.

The initial tests were carried out on SBS PmB. It was not possible to characterise a modified bitumen into the four main groups; saturates, resins, asphaltenes and aromatics using the method available. However, it was possible to characterise an unmodified bitumen. Therefore, to measure what constituents of the bitumen are absorbed by the rubber, two 100 penetration grade bitumens were cured in rubber,

tested in the DSR and Vialit Cohesion Test and then analysed to establish the change in constituents due to the interaction between the bitumen and rubber.

4.2 Mechanical Testing of Residual Bitumen

The rheological properties of bitumen are used to characterise bitumen quality, bitumen ageing, bitumen modification and most importantly bitumen performance. The intention is to identify what effect the rubber is having on the rheological properties of the SBS PmB in the IAA mixture. It is assumed that the residual bitumen collected from the curing tests represents the bitumen in the mixture that has not been absorbed by the rubber and is functioning as the binder in the mixture. If the rubber affects the rheological properties of the residual bitumen it will indicate that the performance of the functioning binder is also changing, possibly causing a lack of adhesion/cohesion in the mixture and reducing the mechanical durability of the mixture.

Samples of residual bitumen have been collected from the swelling tests. These samples have been compared to samples of the same source bitumen that were placed in identical containers but without rubber and cured under the same conditions. Therefore, the changes in rheological properties due to oxidative hardening and evaporation can be monitored and compared to those aged in air and rubber.

4.2.1 Bitumen Rheology

Bitumen is a thermoplastic, viscoelastic liquid that behaves as a glass-like elastic solid at low temperatures and/or rapid loading times (high loading frequencies) and as a viscous fluid at high temperatures and/or slow loading times. At temperatures and loading times between the extremes, the bitumen has properties in the viscoelastic region, exhibiting both viscous and elastic behaviour. The response of bitumen is therefore dependent on both temperature and loading time. The rheology of bitumen is the physical behaviour due to a stress-strain-time-temperature response and is broadly defined as the fundamental measurements of flow and deformation of the bitumen (Airey, 1997).

In the measurement of the rheological properties of bitumen, the time of loading and temperature of loading need to be considered to fully characterise the flow properties of the bitumen. A number of testing apparatus have been developed to test the rheological properties of materials like bitumen that control the temperature and rate of loading. One such test that has shown to give reliable results when characterising conventional and modified bitumens is the Dynamic Shear Rheometer (DSR).

4.2.2 Dynamic Shear Rheometer (DSR) Testing

The DSR is a dynamic oscillatory test that can describe the linear viscoelastic properties of bituminous binders over a range of conditions. It applies a sinusoidal shear strain to a sample of bitumen sandwiched between two parallel disks and is shown schematically in Figure 4.1. The resulting shear stress is monitored through the torque of the top disk as a function of temperature and frequency. Measurements of stiffness and viscosity can be obtained at different temperatures, frequencies and strain levels for samples of bitumen (Airey, 1997). Two of the most important measurements from the DSR are the complex modulus and the phase angle. The absolute value complex shear modulus or $|G^*|$ is the ratio of peak stress divided by peak strain. It represents the absolute value shear stiffness of the bitumen under the conditions of testing and is independent of viscoelasticity. The phase angle or δ is defined as the phase difference between the peak stress and strain. It represents the time delay from applying a stress to when the material responds. A material with a high phase angle represents a highly viscous response, whereas a material with a low phase angle represents an elastic response.

The DSR used in this work was one made by Bohlin. Figure 4.1 shows an illustration of the DSR. The top disc is oscillated through an arc between A to B then back through A to C to generate the sinusoidal stresses and strains. Figure 4.2 shows the definitions of stress, strain and phase angle from a typical DSR trace.

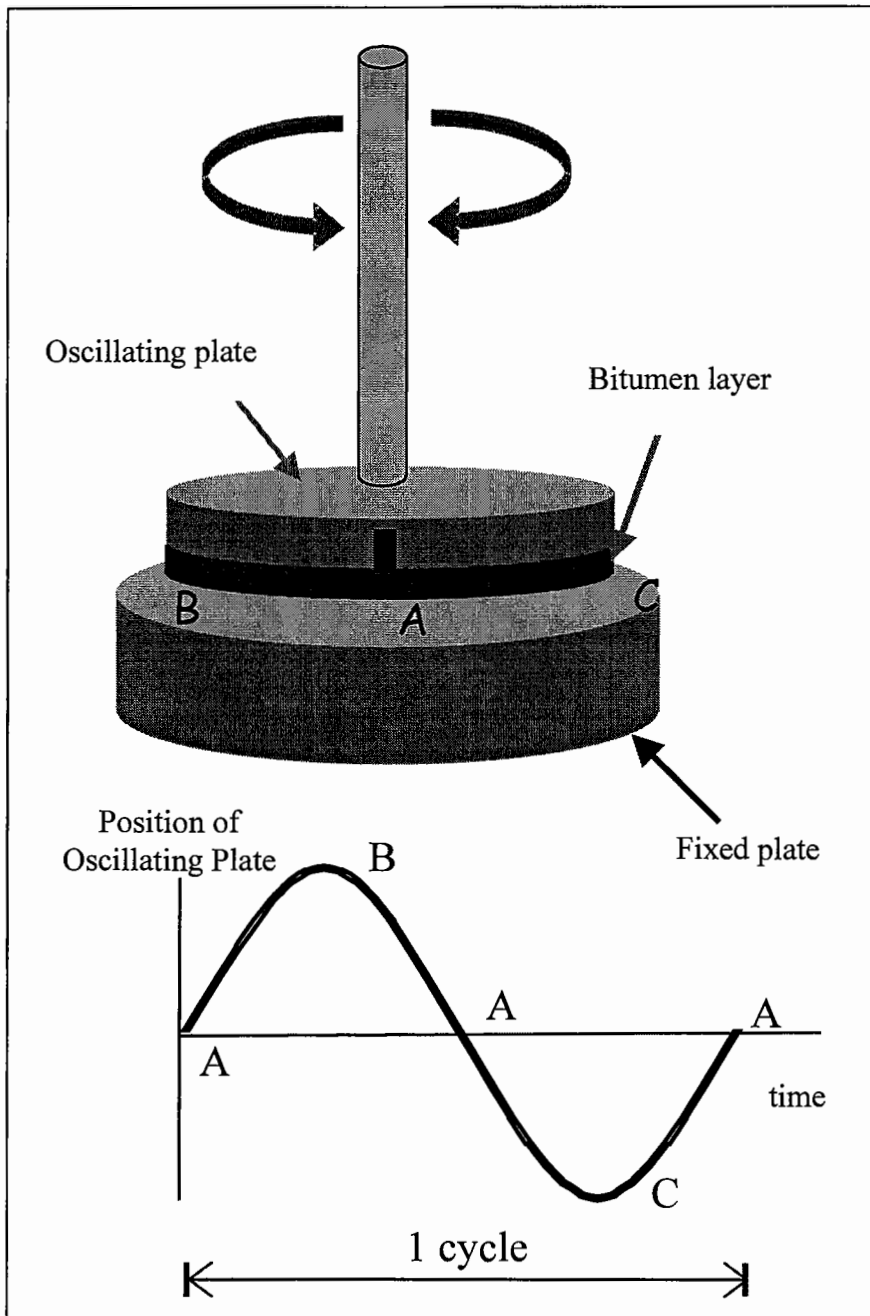


Figure 4.1 - Schematic of the Dynamic Shear Rheometer (DSR) testing configuration

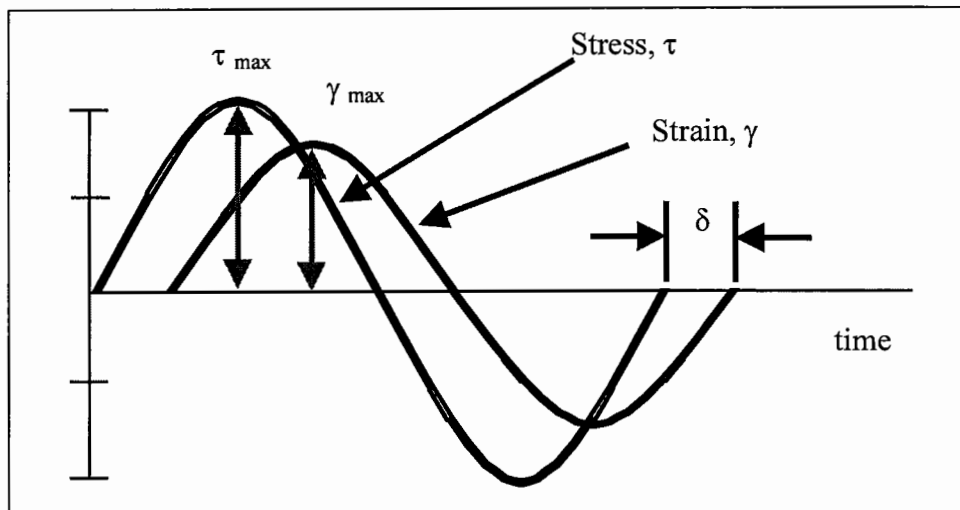


Figure 4.2 - Typical plot of stress and strain in a DSR

The major feature of the DSR is that it has the ability to test bitumen over a range of loading times (frequencies) and temperatures. Typical results from measurements in the DSR of the SBS PmB used in IAA are given in Figures 4.3 and 4.4.

Figure 4.3 gives the measurements of complex modulus of the SBS PmB taken at 35, 45, 55, 65 and 75°C each over a range of frequencies between 0.1Hz and 10Hz. It can be seen that as the temperature increases, the complex modulus, a measure of the stiffness of the bitumen, reduces. Also, a decrease in the loading frequency or increase in the loading time causes a reduction in the stiffness. Figure 4.4 shows the results of phase angle taken at different temperatures and frequencies. The basic trend is a reduction in phase angle for an increase in temperature or a decrease in loading time. This represents a more elastic response, thus a shift in the visco-elastic balance of the bitumen. This trend is typical of a SBS PmB where the SBS polymer substructure becomes more dominant at high temperatures and low loading times (Airey, 1997).

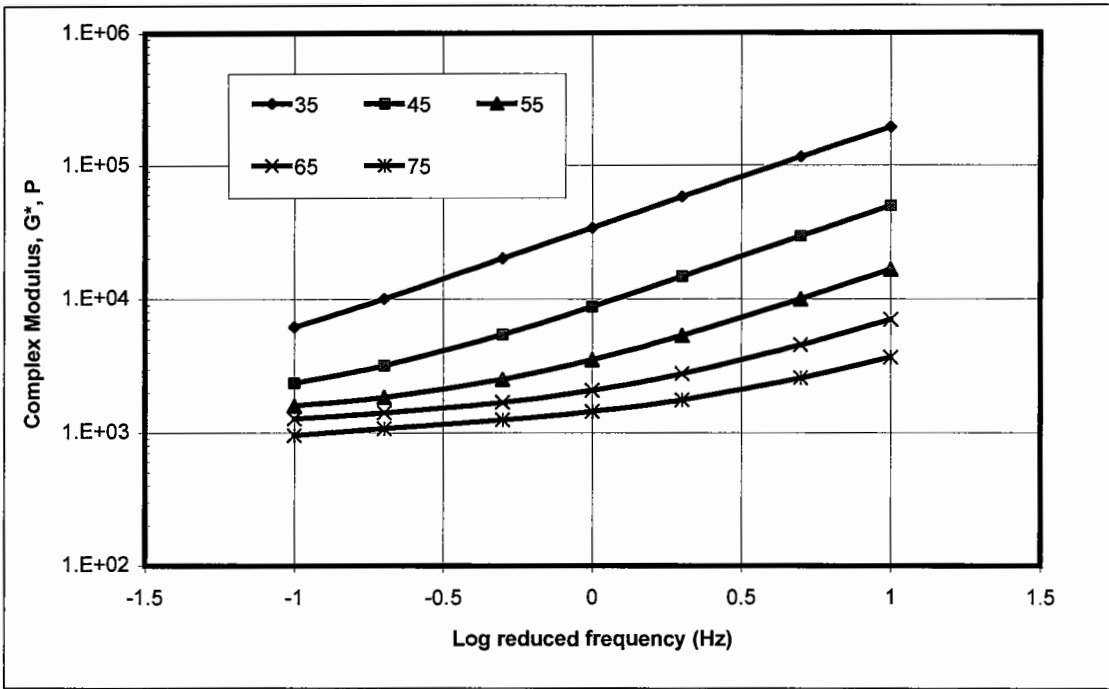


Figure 4.3 - Measurements of Complex Modulus, G^* , taken by the DSR on a sample of SBS PmB

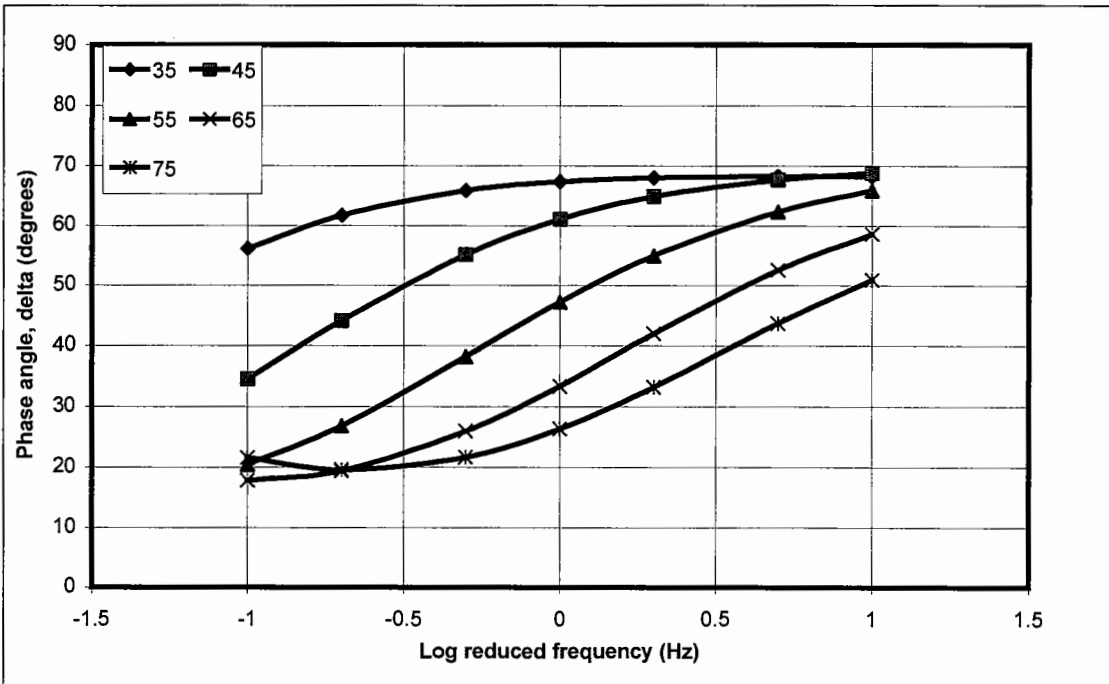


Figure 4.4 - Measurements of Phase Angle (δ), taken by the DSR on a sample of SBS PmB

Construction of Master Curves

The principle advantage of measuring the rheological properties of the bitumen over a range of temperatures and frequencies is that it facilitates the construction of master curves. Work done by various researchers (Ferry, 1971 and Marasteanu and Anderson, 1996) has found that there is an interrelationship between temperature and frequency of loading that, through shift factors, can bring measurements at different temperatures to fit one continuous curve. This curve represents the bitumen behaviour at a given temperature over a large range of frequencies. The one, continuous curve is known as a master curve and the principle used to relate temperature to frequency is known as the time-temperature superposition (Ferry, 1971).

The principle can be demonstrated using the results given above. Figure 4.5 shows the construction of the complex modulus master curve for a set of results presented in Figure 4.3.

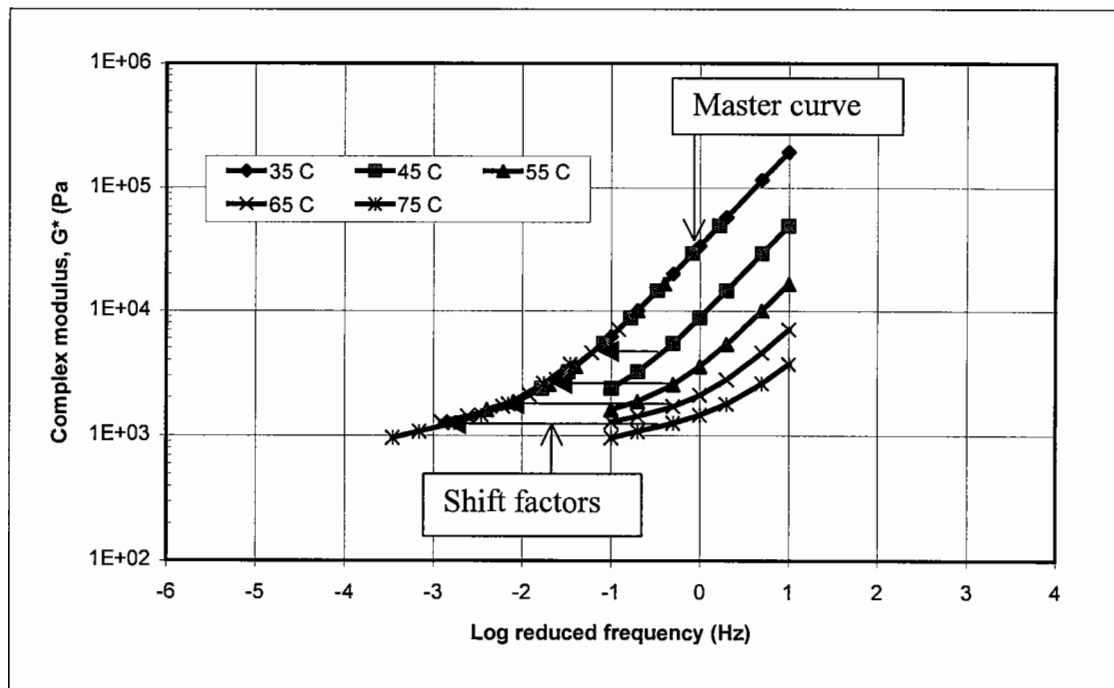


Figure 4.5 - Construction of complex modulus master curve from DSR results for an SBS PmB at a reference temperature of 35°C

Each line representing the complex modulus at a particular temperature has been shifted in the frequency domain to line up with the results measured at 35°C. The magnitude the line is shifted is known as the shift factor. Therefore, the complex modulus master curve represents the behaviour of the bitumen at 35°C between

0.0001Hz and around 10Hz. The same principle can be used to produce a phase angle master curve, as shown in Figure 4.6.

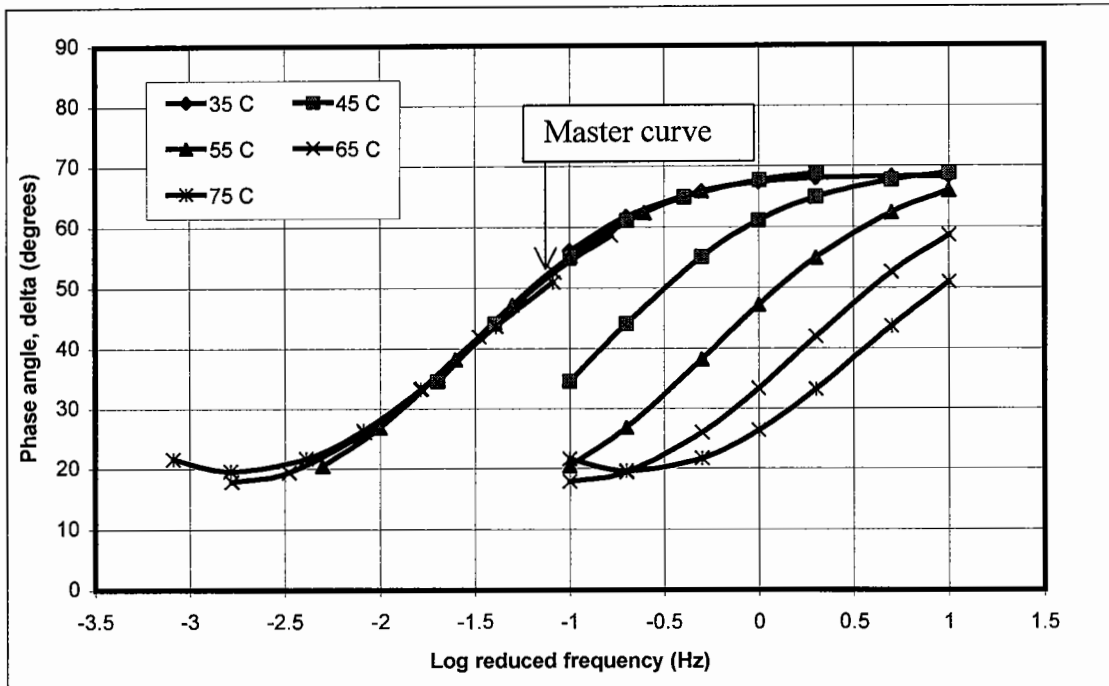


Figure 4.6 - Construction of phase angle master curve from DSR results for an SBS PmB at a reference temperature of 35°C

The advantage of the master curve is that it provides a clearer graphical representation of the bitumen rheology at a particular temperature. The other advantage is that it can represent the behaviour of the bitumen at different temperatures because the reference temperature the master curve is plotted by can be changed to any of the temperatures tested. The response of the bitumen to a long loading time is also representative of its behaviour at a higher temperature and conversely, short loading times represent the behaviour of the bitumen at low temperatures. It is therefore an ideal tool for monitoring the changes in bitumen rheology due to the interaction with rubber.

4.2.3 Method

The intention of this investigation was to measure the changes in rheological properties of the bitumen that has reacted with the rubber and compare them to bitumen that has not reacted with rubber. Analysis of the changes of the rheological properties will help give an indication of what changes occur to the binder in the IAA mixture through the interaction with the rubber.

Sample Collection

The bitumen samples tested were collected from the curing tests using 6-9mm crumb rubber by draining them through a sieving grid. Three samples of residual bitumen were collected that had been soaked in 33% rubber for 1, 6 and 24 hours each. Also, 3 samples of bitumen from the same batch of bitumen were aged in the oven in identical beakers without any rubber added for each ageing period. One sample cured without rubber was removed for each rubber cured sample. Therefore, there was a direct comparison between samples that had been aged in the same way but one with rubber and one without. It should be noted that all the solid crumb rubber had been removed from the bitumen by the sieving grid before testing, so the comparison is directly between oven aged and rubber aged SBS PmB, unless some of the crumb rubber had dissolved into the bitumen. Unfortunately, the movement of components or particles of the rubber into the bitumen cannot be assessed without chemical analysis and is out of the scope of the work.

Sample Preparation

Sample preparation consists of heating samples of residual or cured bitumen to 185°C and pouring the sample onto the bottom disk of the DSR. The top disk is then lowered to give a 1.05mm thick layer of the bitumen sample between the disks before the sample is trimmed to remove excess bitumen outside the radii of the disks. The upper disk is then lowered a further 0.05mm so that the distance between the disks was 1mm and the open edge of bitumen is concave. Each sample was tested under the following conditions.

- Temperatures: 35, 45, 55, 65 and 75°C
- Frequencies: 0.1, 0.2, 0.5, 1, 2, 5 and 10Hz
- Maximum strain level = 0.1%
- 25mm diameter parallel disks

The data for each sample was then collected and analysed. The three samples taken for each condition, were compared and averaged to give an average result. The results

were then plotted in the form of master curves for the complex modulus and phase angle.

4.2.4 Results

SBS PmB has a distinct mechanical property (Airey, 1997). The two phase system in SBS PmB means that, at low temperatures and high frequencies where the bitumen is stiffer and less fluid, the mechanical performance of the bitumen blend is dependant on the properties of the bitumen. For a conventional bitumen, as the temperature is increased and the frequency is decreased the bitumen becomes more fluid. Hence, the complex modulus decreases and the phase angle increases. However, SBS PmB under these conditions does not reduce in stiffness to the same degree and inhibits a decrease in phase angle representing a more elastic response. This is due to the action of the SBS polymer in the bitumen blend; as the bitumen becomes more fluid, its mechanical properties become less dominant and the elastic properties of the SBS polymer substructure become more dominant. Therefore, it is possible to investigate the effect of rubber ageing on the polymer and the bitumen by analysing the mechanical behaviour of the bitumen under these two extreme measured conditions. On the master curves, a high frequency response represents the bitumen dominant phase and a low frequency response represents the polymer dominant phase.

Figures 4.7 and 4.8 show the complex modulus and phase angle master curves for two samples of SBS PmB cured without rubber, one for 1 hour and one for 24 hours at 155°C. The results show that curing the SBS PmB at a high temperature increases the complex modulus at high loading frequencies where the properties of the bitumen are more dominant. However, at low loading frequencies, where the properties of the polymer structure are more dominant, the curing decreases the complex modulus. The measurements of the phase angle in Figure 4.8 show that at low frequencies, the bitumen tends towards a more viscous response through ageing. These properties are indicative of oxidative ageing of a SBS PmB and are discussed later.

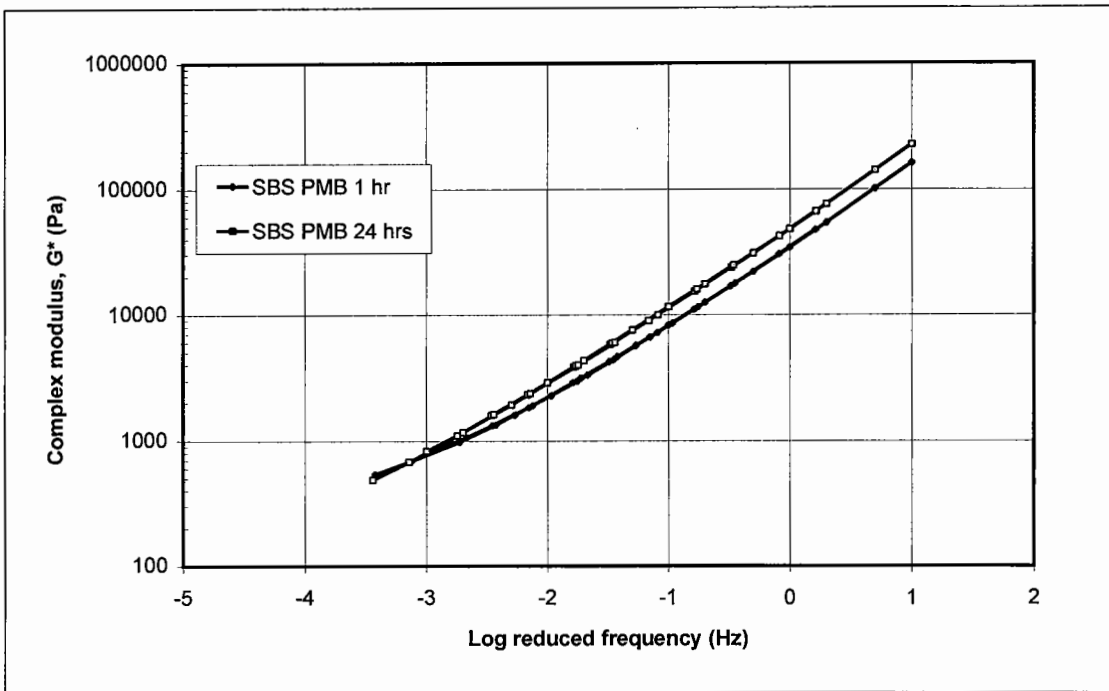


Figure 4.7 - Complex modulus master curves for SBS PmB cured at 155°C without rubber

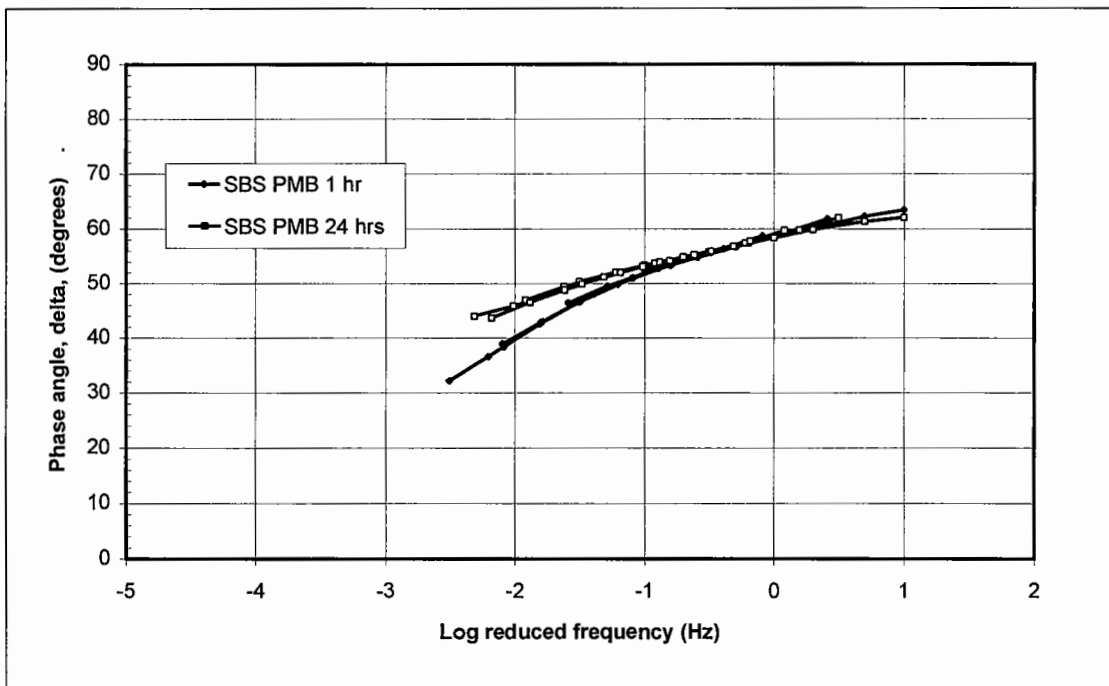


Figure 4.8 - Phase angle master curve for SBS PmB cured at 155°C without rubber

Curing the bitumen at a high temperature changes the properties of the bitumen. To assess if there is an additional effect due to the interaction between the rubber and the

bitumen, the samples of residual bitumen from the rubber curing tests were tested. The measurements of complex modulus and phase angle are presented in Figure 4.9 and 4.10 respectively.

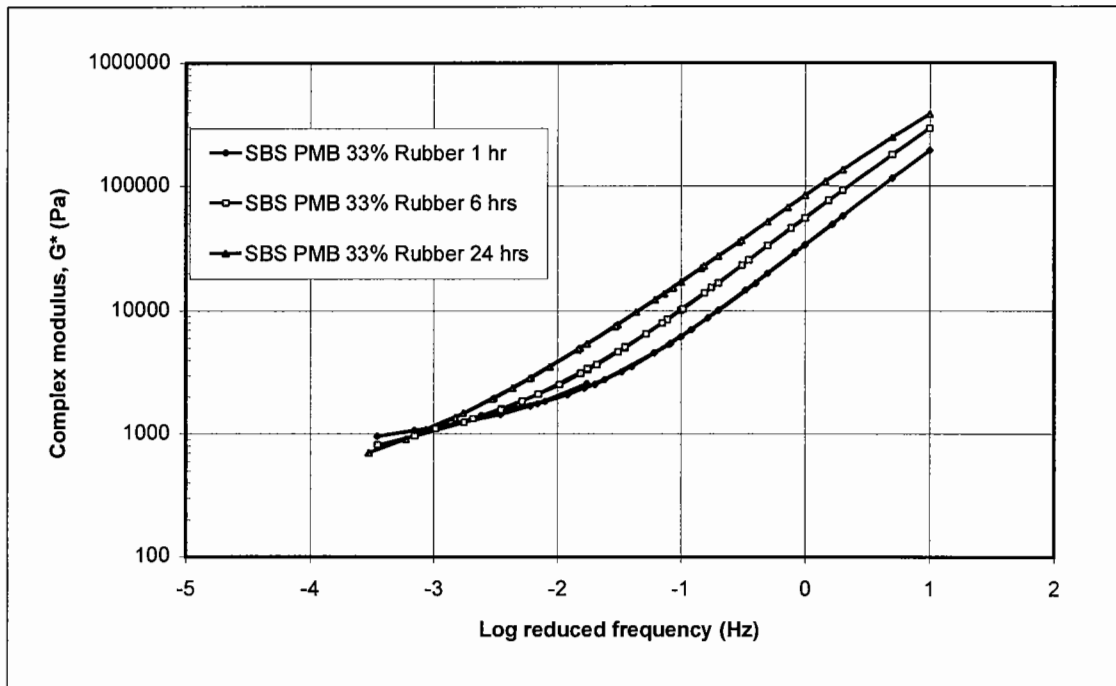


Figure 4.9 - Complex modulus master curves for residual SBS PmB cured with 33% rubber at 155°C

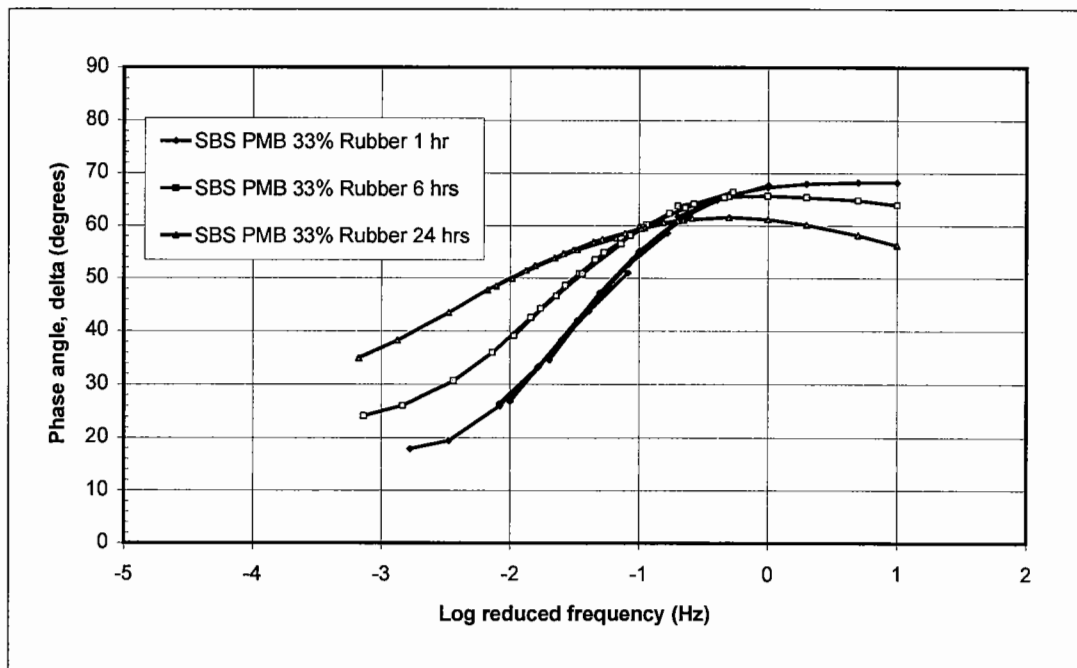


Figure 4.10 - Phase angle master curves for residual SBS PmB cured in 33% rubber at 155°C

Figure 4.9 presents three complex modulus master curves that were taken from measurements of the residual bitumen that had been aged in crumb rubber. At high frequencies, ageing of the bitumen in rubber increases the stiffness. At low frequencies, the interaction with rubber with time is decreasing the stiffness of the bitumen.

A more pronounced difference is noticeable with the phase angle master curves for the same series of tests shown in Figure 4.10. At the bitumen dominant stage, the ageing of the bitumen with rubber decreases the phase angle meaning an increase in elastic behaviour of the bitumen. At the polymer dominant stage on the other hand, the ageing of the bitumen in rubber increases the phase angle, resulting in a more viscous behaviour at these conditions suggesting that the polymer is becoming less effective in the bitumen/polymer blend.

A direct comparison between the samples aged at 24 hours in rubber and for 24 hours without rubber illustrates the magnitude of the effect of the rubber on the properties of the residual bitumen.

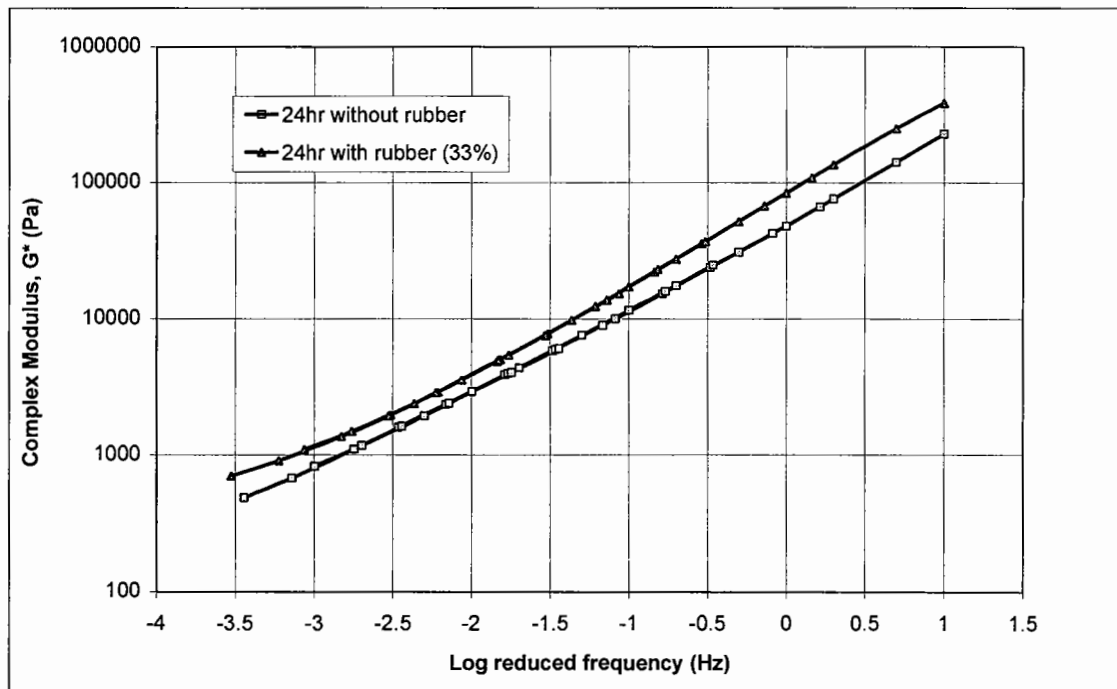


Figure 4.11 - Comparison of complex modulus for SBS PmB cured in rubber and no rubber for 24 hours

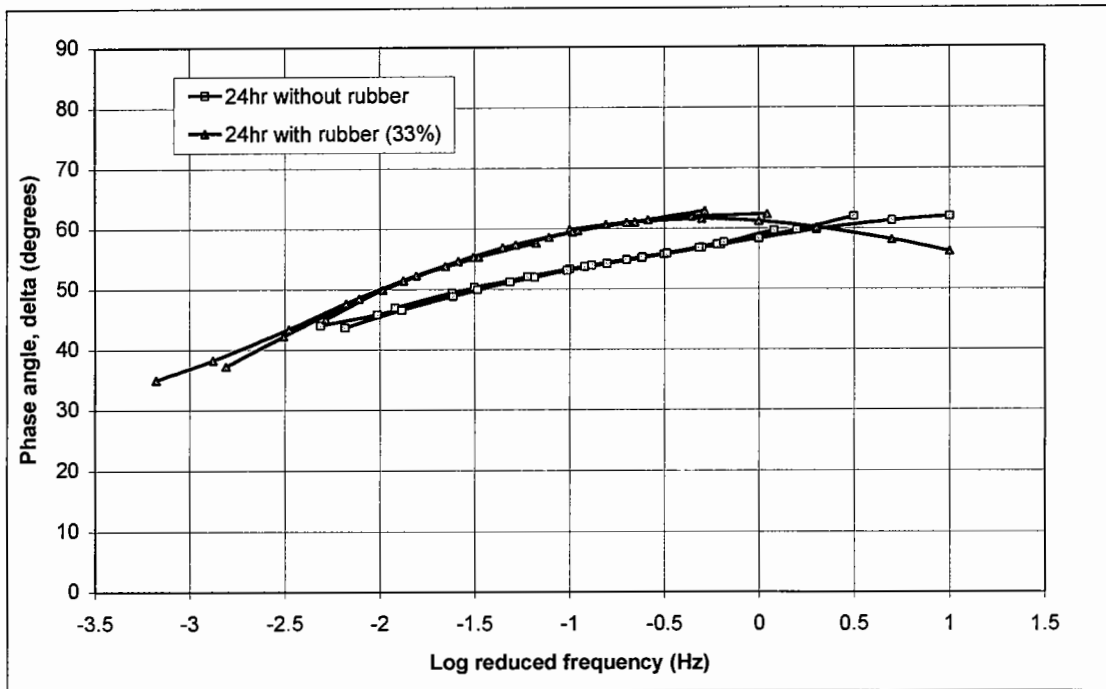


Figure 4.12 - Comparison of phase angle for SBS PmB cured in rubber and without rubber for 24 hours

4.2.5 Discussion

To understand the changes in mechanical properties due to the interaction with rubber, the process of bitumen ageing should be understood. When bitumen ages in air it hardens and the main component of hardening is oxidation. The oxidation of bitumen involves oxygen reacting with the more reactive components of the bitumen, producing compounds of high polarity. These high polar compounds form micelles due to molecular attractive forces that have a high molecular weight. Therefore, the proportion of high molecular weight micelles in the bitumen increase thus causing gellification, increasing the stiffness and hardening the bitumen. Another process that will harden the bitumen is the evaporation of the more volatile components of the bitumen. The magnitude of hardening is dependent on the amount of lighter molecular weight fractions in the bitumen (Whiteoak, 1990).

The curing of the bitumen in containers at 155°C without rubber will accelerate the hardening process due to the high temperature making the components more reactive. Only the surface of the bitumen will react with oxygen, so the magnitude of hardening is not likely to be great. This is illustrated in the results at the bitumen dominant stage

for the samples aged without rubber, as the change in complex modulus and phase angle is not significant at 10Hz. The change in behaviour of the samples cured without rubber at the lower frequencies, i.e. the polymer dominant stage, suggest a degradation of the SBS polymer substructure. The complex modulus is decreased through ageing at this condition and the phase angle is increased, a shifting towards more viscous, fluid-like behaviour. This phenomenon has been observed by other researchers (Airey, 1997 and Kuppens, 1995) and is thought to be because the SBS substructure fragments through the action of oxygen and heat, reducing its effect on the properties of the bitumen and a loss of compatibility between the polymer and the bitumen.

The curing of the SBS PmB in the rubber appears to be enhancing the hardening of the bitumen. The inclusion of rubber increases the complex modulus of the bitumen throughout the visco-elastic region as shown in Figure 4.11. The reason for this is thought to be due to the rubber absorbing the lighter molecular weight fractions of the bitumen. Rubber will absorb lower molecular weight compounds more readily because they can diffuse more quickly into the rubber matrix. The reduction of lighter molecular weight fractions in the bitumen increases the proportion of the higher molecular weight compounds and thus increases the stiffness of the bitumen. This may have an effect on the compatibility of the bitumen with the SBS polymer as the balance of fractions will change and the evidence suggests that the polymer is becoming less dominant as the PmB is cured in rubber. However, it is difficult to assess what components are being absorbed and what is happening to the SBS substructure by looking at the SBS PmB alone. Therefore, a further investigation using conventional bitumens was carried out to understand the interaction between the rubber and the bitumen.

Summary

The interaction between the rubber and the bitumen has been shown to affect the rheological properties of the residual bitumen (as measured by the DSR) because the composition of the bitumen is changing. It is believed that the compounds with a lower molecular weight will more readily diffuse into the rubber, thus leaving the residual bitumen with a larger proportion of heavy molecular weight compounds. The

increase in the proportion of the heavy molecular weight compounds causes an increase in the stiffness of the bitumen, leaving the bitumen with a higher viscosity. The next stage is to investigate how these changes manifest themselves in the performance of the bitumen as a binder by measuring the changes in cohesion.

4.3 Cohesion Testing of Residual Bitumen

Cohesion and adhesion are two parameters that represent the ability of the bitumen to bind aggregate and rubber together in a strong matrix. They, therefore represent the ability of the bitumen to bind the aggregate and the rubber. Cohesion is the ability of a material to 'stick' to itself and adhesion is the ability of the material to 'stick' to another material. Adhesion is dependent on the properties of both the materials coming into contact and is a difficult parameter to measure. However, because cohesion is a measure of the materials own ability to stick together it can be measured empirically. The Vialit Pendulum Cohesion test is an empirical measure of the cohesive strength of bitumen. It is designed to measure the ability of the bitumen to 'stick' together and is not a measure of the adhesive strength of the bitumen. Cohesion is defined in the Manual of Contract Documents for Highways Works Clause 939 as "the energy per unit area which is needed to break a film of bituminous binder under specified conditions of impact." [Manual, 1992].

4.3.1 Method

The test equipment consists of a pendulum that is raised to the vertical and is allowed to drop through its arc to strike a steel cube (see Figure 4.13). The steel cube is fixed to a plate by a 1mm thick layer of bitumen. The bitumen adheres to the cube and the plate over a 1cm² area. The steel block is dislodged by the impact of the pendulum. Upon striking the block, the bitumen is ruptured and the kinetic energy of the pendulum is absorbed. The amount of energy absorbed is determined by the angle swept by the pendulum after breaking the cohesive bonds of the bitumen.

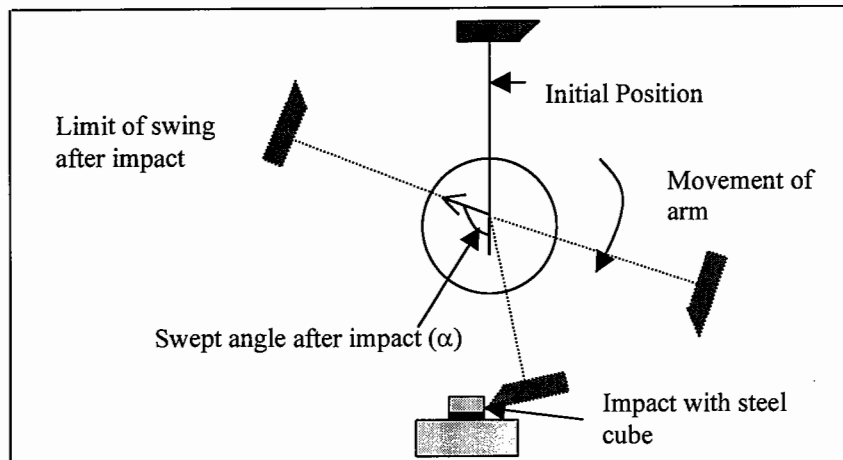


Figure 4.13 - Schematic of the Vialit Pendulum Cohesion Test.

To ensure that the cohesion of the binder is measured in the test, the surfaces of the block and the plate are serrated with grooves to increase the contact area between the bitumen and the steel and increase the adhesive strength of the steel/bitumen bond.

Test Procedure

The intention of the test is to find the optimum energy absorbed by the bitumen in the impact. This translates as the smallest angle swept by the pendulum through a series of temperatures. The 1cm^2 of bitumen is the assumed fracture area when the pendulum impacts the steel block. Therefore, the impact energy can be calculated knowing the mass and radius arm of the pendulum. To calculate the energy absorbed the following equations are used;

$$E_T = MgR(1 + \cos \alpha) = E_B + E_K \quad 4.1$$

where;

E_T = total energy absorbed in breaking the binder and in imparting kinetic energy to the detached cube

M = mass of the pendulum

g = acceleration due to gravity

R = radius of the centre of gravity of the pendulum

α = swept angle after impact of the pendulum in degrees (0 degrees corresponds to the lowest position)

E_B = energy absorbed in breaking the binder

E_K = energy absorbed in imparting kinetic energy to the detached cube

To calculate E_B , the energy absorbed in breaking the binder, the value of E_K can be measured by carrying out the same procedure without any binder present between the steel cubes.

The cohesive value of the binder is in the form of energy per unit area, and is given by;

$$C = \frac{E_B}{A} \quad 4.2$$

where;

C = cohesion value (J/cm^2)

A = area of cube = 1 cm^2

The test is carried out over a range of temperatures and the cohesion value results are plotted against temperature on a linear scale to give a plot similar to Figure 4.14.

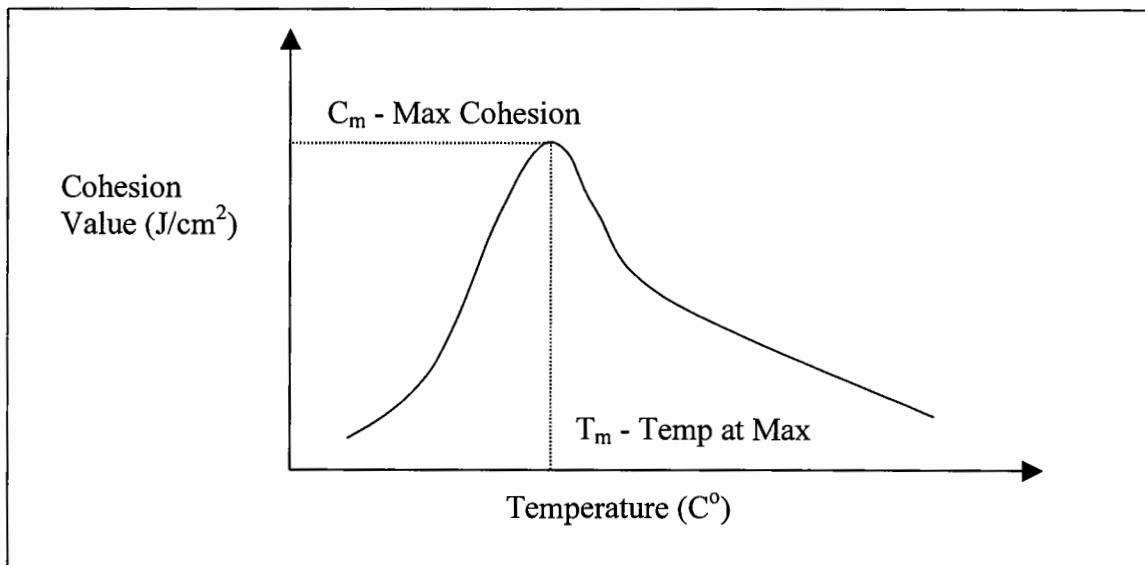


Figure 4.14 - Idealised Cohesion Value-Temperature Plot

The failure at temperatures below the temperature at max cohesion is said to be a brittle fracture and above that temperature the fracture is more viscous.

4.3.2 Results

Figure 4.15 shows a cohesion-temperature plot for 0 hours and 24 hours aged SBS PmB in the oven and 24 hours aged SBS PmB in rubber. The maximum cohesion values for the 'no rubber aged' samples is not affected through ageing, but the temperature at which the maximum cohesion occurs for the 24 hour aged sample is slightly increased suggesting a tendency to more brittle behaviour which is consistent with the properties of bitumen when aged. The 24 hour 'rubber aged' sample shows a similar shift in the temperature of maximum cohesion, but the cohesion value is also reduced. Therefore, ageing of the SBS PmB in rubber has reduced the cohesion of the bitumen. This result helps to explain the reduction in durability of the material as it ages in the rubber.

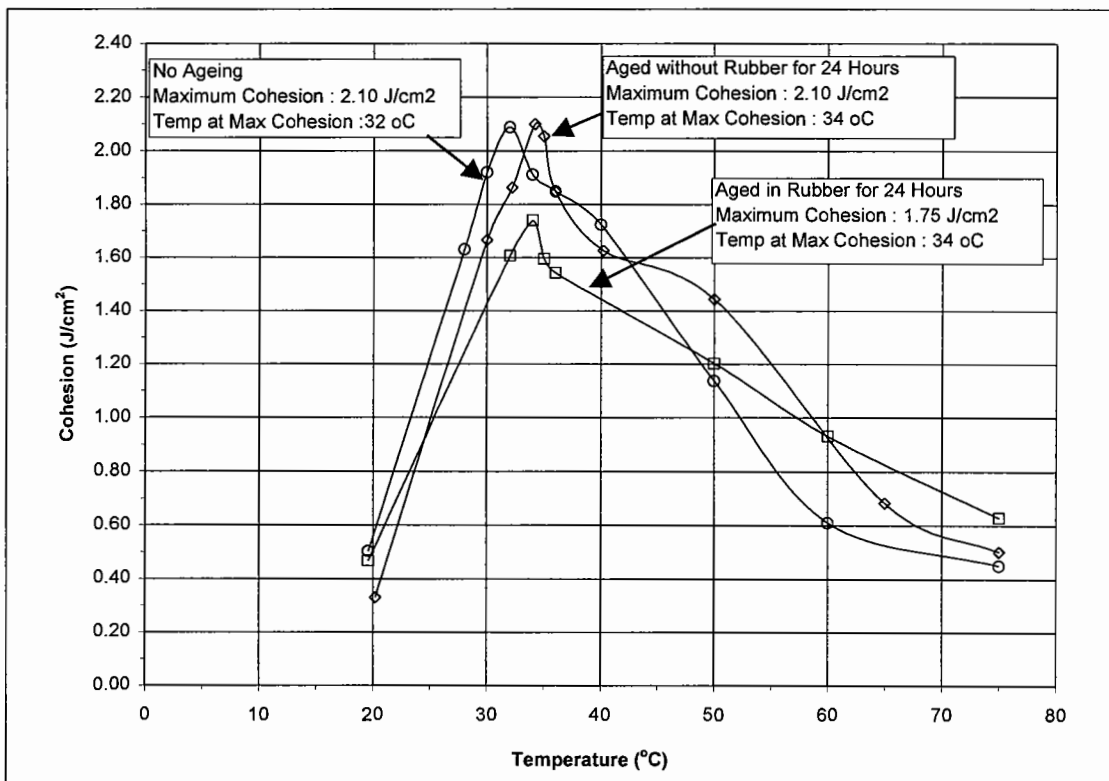


Figure 4.15 - Cohesion curves for different samples of residual SBS PmB

4.3.3 Summary

The results have shown that the cohesion of the SBS PmB is reduced because of the introduction of rubber to the mixture. This correlates to a change in the rheological

properties due to the interaction with the rubber where the residual bitumen is becoming stiffer and more elastic. The hypothesis for these changes is that the rubber is absorbing the lighter fractions of the bitumen, changing the colloidal structure of the bitumen. For SBS PmB this is making the bitumen incompatible with the polymer and thus diminishing the efficiency of the modified binder as it has lower proportion of aromatics to support the SBS substructure in the bitumen. Therefore, the properties of the SBS are becoming less dominant at low frequencies, which is illustrated in the results presented on the rheological properties of the rubber cured specimens. However, because it is not possible to assess what the rubber is absorbing solely through interpretation of the rheological results and cohesion results, an investigation of the changes in the bitumen constitution has been carried out. The chosen method to monitor the bitumen constitution is termed a SARA analysis. It measures the proportions of Saturates, Asphaltenes, Resins and Aromatics in the bitumen by using thin film chromatography (Morgan and Mulder, 1995). Unfortunately, the method could not be carried out on a SBS PmB, so unmodified 100 penetration grade bitumens were used.

4.4 Analysis of conventional bitumen-rubber interaction

The following section investigates the change in bitumen composition due to the interaction with crumb rubber of two 100 Penetration grade bitumens. It compares the changes in bitumen constitution with the change in rheological properties and cohesion, to aid in understanding what is happening to the SBS PmB when it reacts with the crumb rubber.

4.4.1 Binder Absorption Tests

Two different 100 penetration grade bitumens, A and B were chosen to investigate the effect of the composition of the bitumen on the interaction with the rubber and the change in mechanical properties. Bitumen A had a high aromatic content and low asphaltene content and Bitumen B has a low aromatic content and a high asphaltene content. Bitumen A represents the base de-asphalted bitumen used in producing the SBS modified bitumen. Curing tests in rubber were undertaken to assess if the bitumen composition affects the rate of rubber-bitumen interaction.

The tests were designed to investigate the maximum amount of bitumen that the rubber could absorb. The rate of swelling was also monitored to give an indication of the rate of the interaction.

Method

The same curing tests used to investigate the effect of concentration on the interaction between the rubber and SBS-bitumen were used for Bitumens A and B. The rubber-bitumen ratio in the each beaker was 33% (10g of 6-9mm graded rubber to 20g of bitumen). Sets of seven beakers were prepared for both bitumens and within each set, each beaker was allowed to cure for a different time. Upon completion of draining, the system was removed from the oven and allowed to cool. The swollen rubber was then removed from the gauze and weighed. The residual bitumen was stored at 5°C for further testing.

Results

The results for the curing tests are shown in Figure 4.16 where the percentage increase in the mass of the rubber is plotted against curing time for both bitumens. It can be seen from the figure that the amount of swelling increases with time. This confirms that the rubber is absorbing bitumen solvent resulting in an increase in mass. The negligible difference in the absorption curves for the two bitumens suggests that the bitumen composition has a limited affect on the rate of interaction with the rubber indicating that other factors such as the temperature and type of rubber have a larger influence on the interaction. The data shows that Bitumen A, which has the higher aromatic content, is being absorbed less by the rubber than Bitumen B. However, the difference is negligible and maybe attributed to experimental error. Therefore the rate of interaction for the two bitumens will be assumed equal and not affected by the difference in composition.

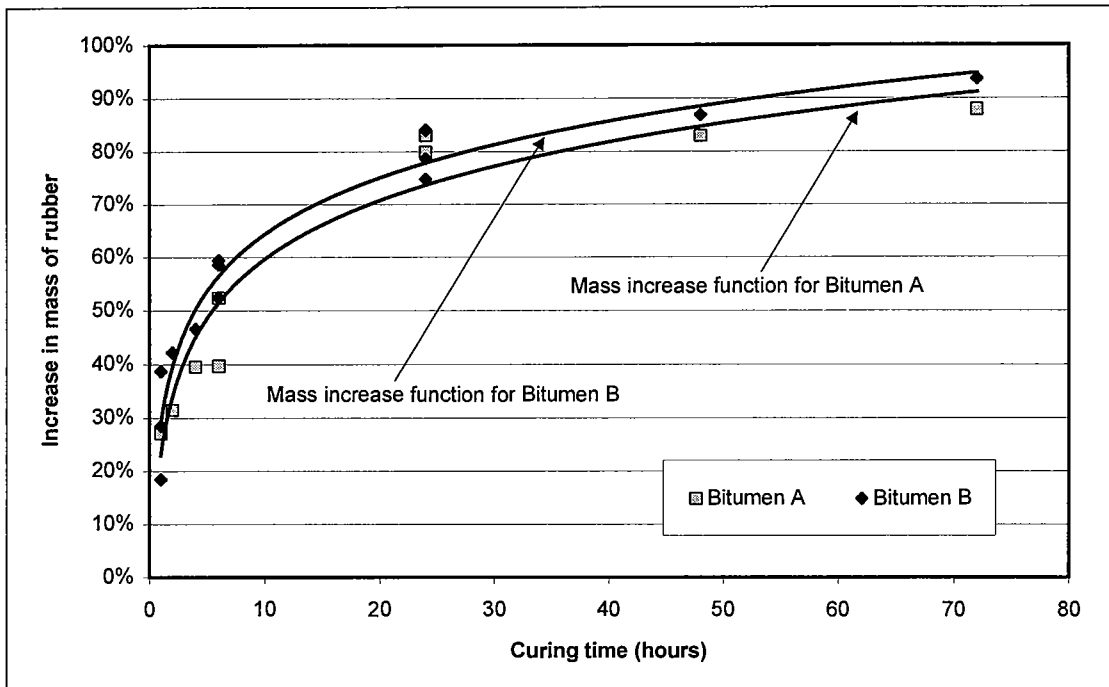


Figure 4.16 - Increase in mass of 100 penetration grade Bitumens A and B at 155°C

4.4.2 Bitumen Constitution

It has been reported that rubber will absorb the lighter (maltene) fractions of the bitumen more readily [Vonk and Bull, 1989], leaving a higher proportion of asphaltenes in the residual binder and thus change the rheological properties of the residual binder.

The residual samples of bitumen from the curing tests were collected and an analysis by thin film chromatography was carried out to determine the bitumen constituents; Saturates, Aromatics, Resins and Asphaltenes. This process is often termed SARA analysis (Morgan and Mulder, 1995).

Samples of each bitumen were cured at 155°C in 33% rubber for 1, 6 and 24 hours. The effect of the rubber in the bitumen was monitored and was compared with samples cured for the same period but without any rubber as a control. The SARA analysis for the Bitumen A is given in Figure 17. Bitumen A was chosen to represent a low asphaltene and high aromatic content bitumen.

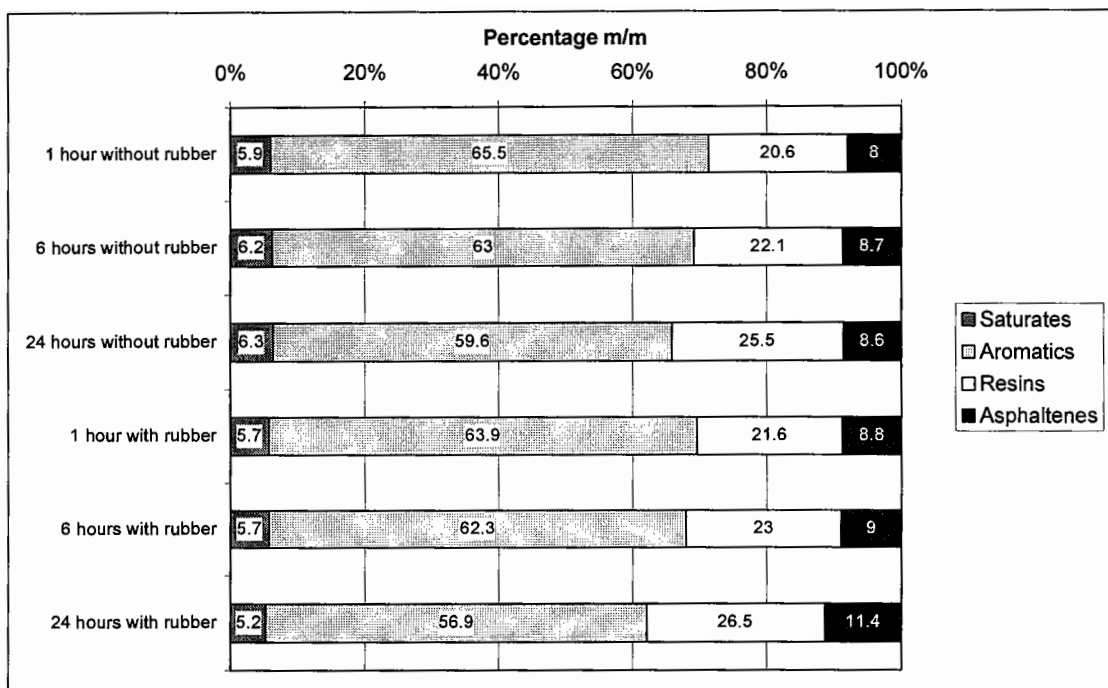


Figure 4.17 -SARA analysis on Bitumen A cured in rubber and no rubber

The samples cured without rubber demonstrate a decrease of aromatics and an increase in resins. The saturate and asphaltene contents are relatively constant. These changes can be attributed to oxidation of the sample that occurs because of the high temperature associated with the curing test.

Bitumen A cured in the rubber shows a decrease in the aromatic and saturate contents and an increase in the resin and asphaltene contents. Assuming that any changes from that seen for the samples cured without rubber can be attributed directly to the influence of the crumb rubber, it can be seen that the crumb rubber is absorbing mostly the saturate and aromatic fraction from the bitumen. This fraction represents the molecules with the lowest molecular weight and suggests that the rubber more readily absorb the smaller molecules.

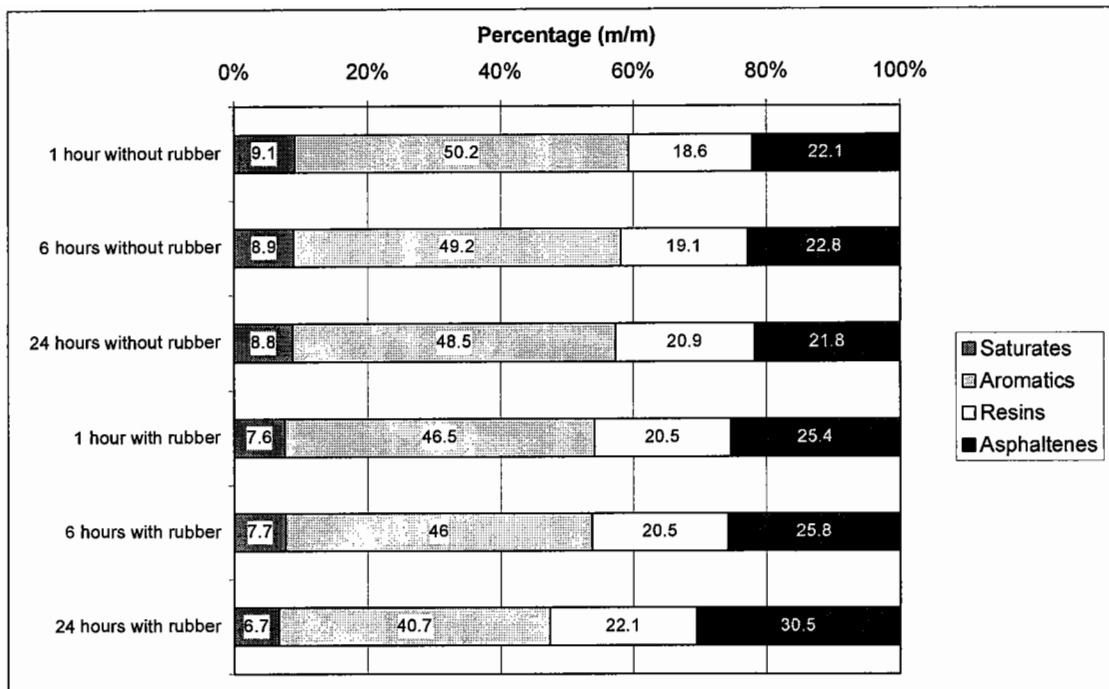


Figure 4.18 - SARA analysis Bitumen B cured with and without rubber

Figure 4.18 presents the SARA data on Bitumen B that was chosen to represent a bitumen with a high asphaltene content and low aromatic content. The results show a similar pattern to Bitumen A with the aromatic content decreasing and the resin content increasing for the cured samples without rubber, while the saturate and asphaltene contents remain relatively unchanged. The rubber cured samples show a greater decrease in aromatic and saturate contents and increase in the asphaltene and resin contents than Bitumen A.

4.4.3 Rheological Properties

Method

Samples of each bitumen were prepared and placed in 50ml containers that were then placed in a force draft oven at 155°C. Three containers were used for each bitumen with 33% and 0% rubber and aged for 1, 6 and 24 hours. The samples were then allowed to cool and placed in a temperature controlled cabinet at 5°C until they were ready to be tested.

Results on Bitumen A

The results are presented in the form of complex modulus and phase angle master curves. This represents the behaviour of the bitumen at 45°C for a range of loading frequencies based on a time-temperature superposition. This temperature was chosen because it is closest to the temperature of maximum cohesion measured using the Vialit Pendulum and described later in this chapter. The measured values of the complex modulus and phase angle for the air cured samples of 100 penetration grade bitumen are presented in Figures 4.19 and 4.20. The rubber cured samples for the same bitumen are shown in Figures 4.21 and 4.22.

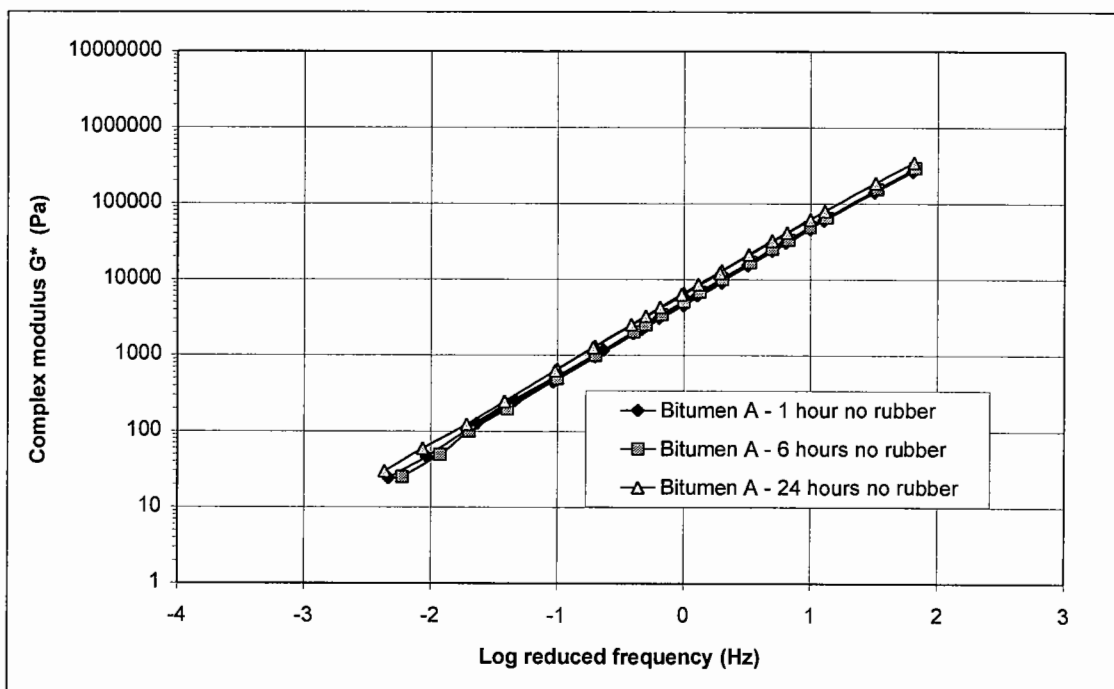


Figure 4.19 - Master curves of complex modulus at reference temperature 45°C for 100 Pen Bitumen A cured without rubber for 1,6 and 24 hours at 155°C

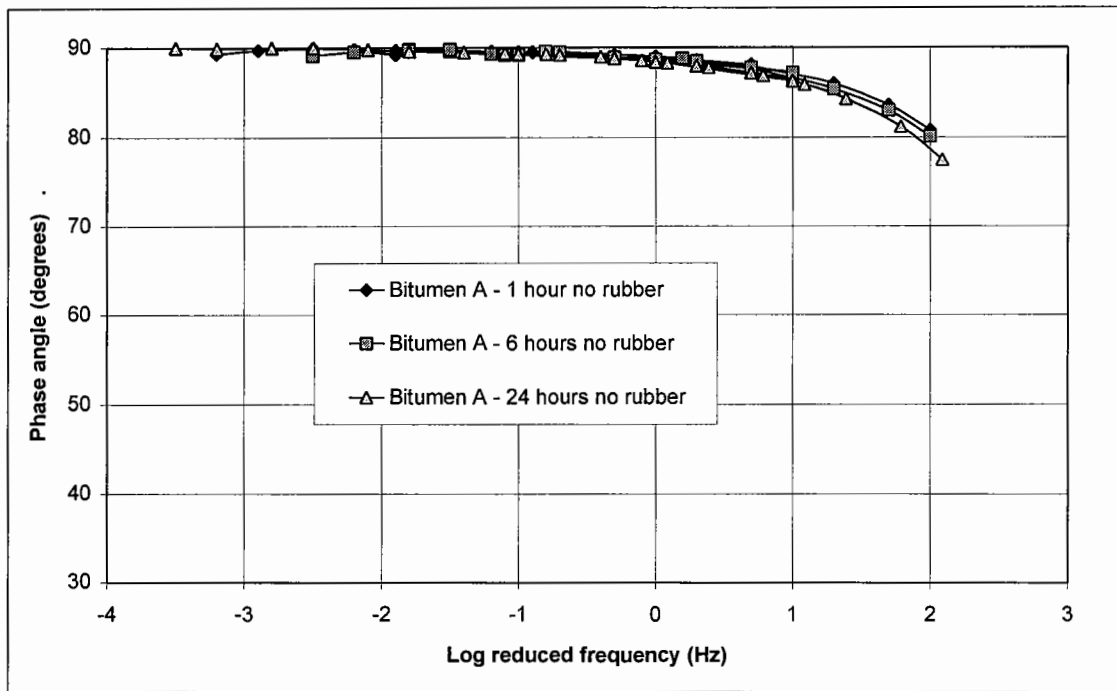


Figure 4.20 - Master curves of phase angle at reference temperature 45°C for 100 Pen Bitumen A cured without rubber for 1,6 and 24 hours at 155°C

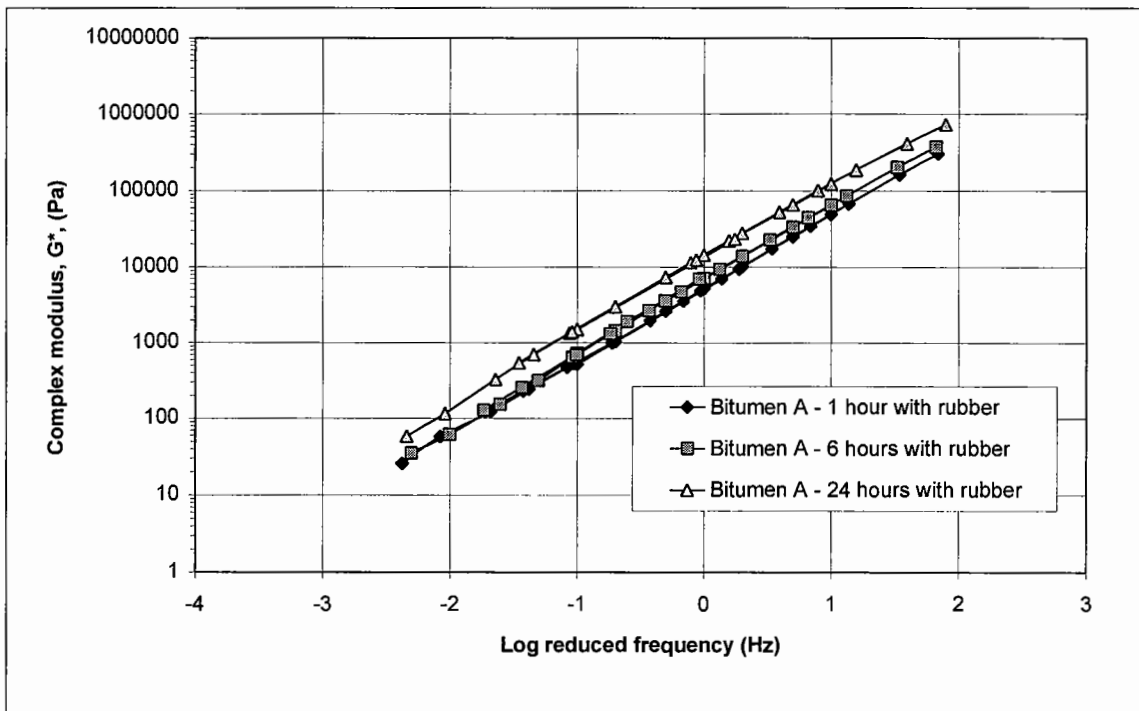


Figure 4.21 - Master curves of complex modulus at reference temperature 45°C for 100 Pen Bitumen A cured with rubber for 1,6 and 24 hours at 155°C

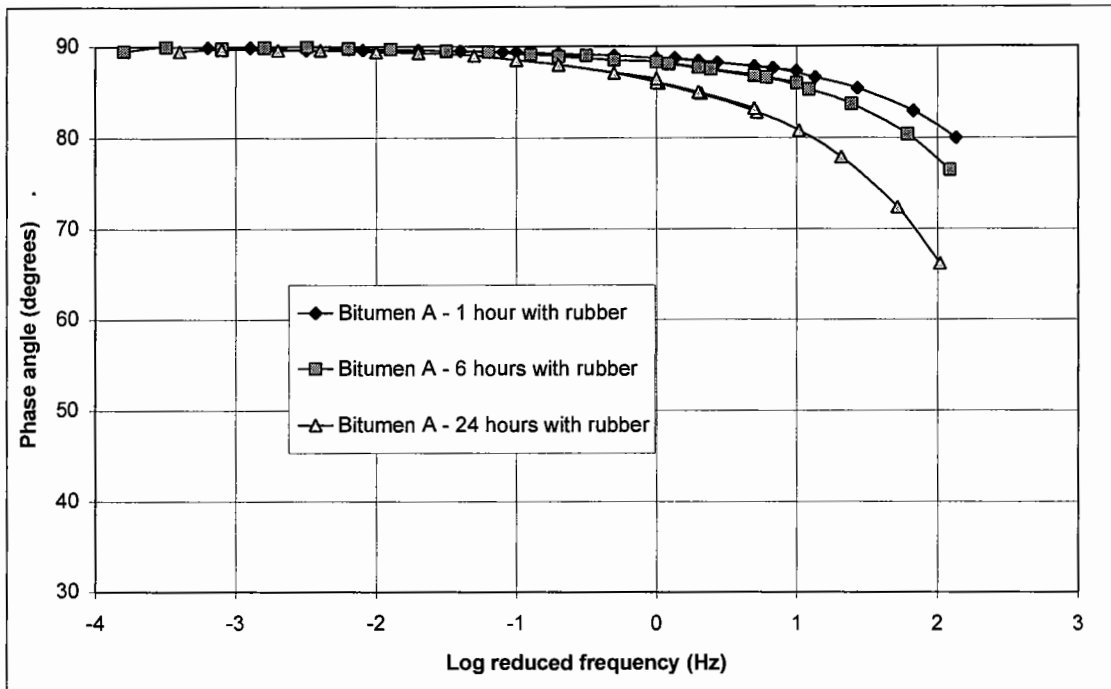


Figure 4.21 - Master curves of phase angle at reference temperature 45°C for 100 Pen Bitumen A cured with rubber for 1,6 and 24 hours at 155°C

The samples of bitumen cured without rubber show a slight increase in complex modulus and a slight decrease of phase angle over the range of loading frequencies. This behaviour can be attributed to the oxidation of the bitumen at high temperatures resulting in increased stiffness of the bitumen and its response to loading becoming more elastic.

The samples of bitumen cured with the rubber show a larger change in the rheological properties. The complex modulus (stiffness) is increased by a factor of 2.8 at a loading frequency of 1Hz when the bitumen is aged for 24 hours in rubber compared to 1.4 for the bitumen cured without rubber. The phase angle also shows a larger decrease for the rubber cured bitumen, especially at the higher loading frequencies, tending towards a more elastic response. This illustrates that in addition to the effects of oxidative ageing the rubber is absorbing the lighter fractions of the bitumen and thereby increasing the stiffness and elastic response of the resulting residual bitumen.

Results on Bitumen B

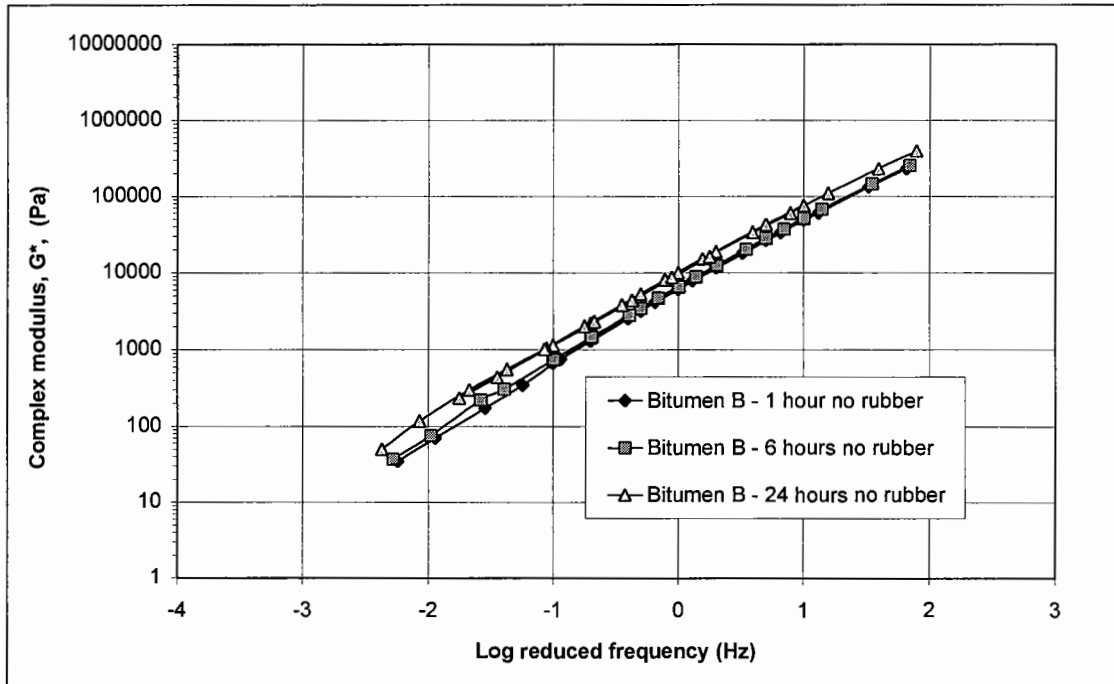


Figure 4.23 - Master curves of complex modulus at a reference temperature of 45°C for 100 Pen Bitumen B cured without rubber for 1, 6 and 24 hours at 155°C

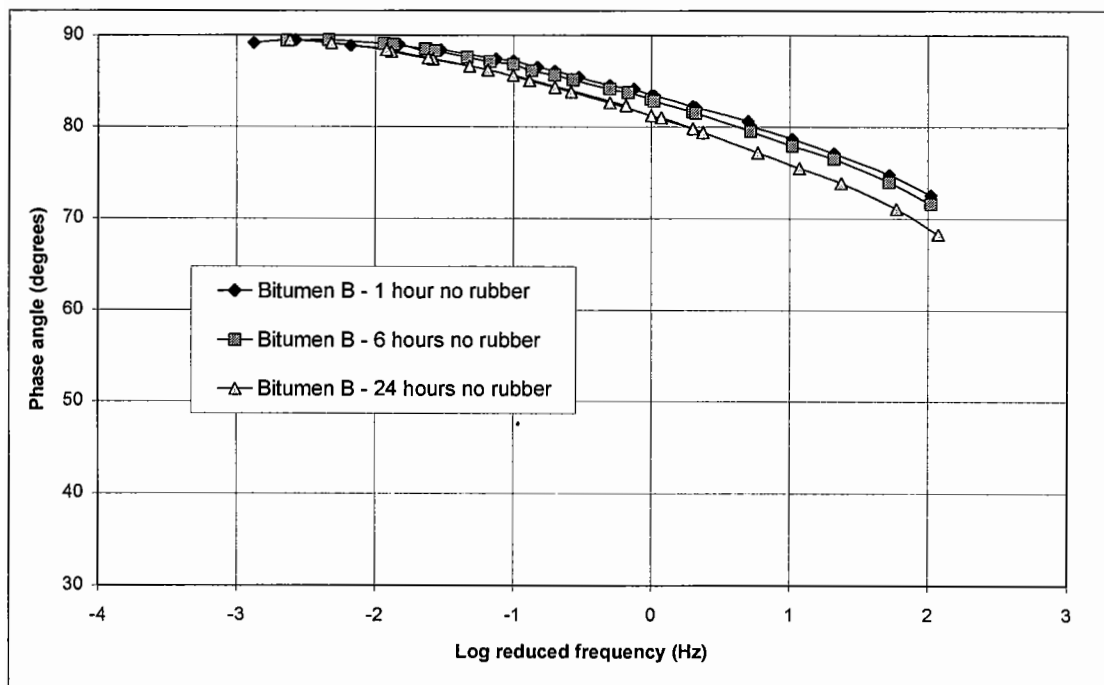


Figure 4.24 - Master curves of phase angle at a reference temperature of 45°C for 100 Pen Bitumen B cured with rubber for 1, 6 and 24 hours at 155°C

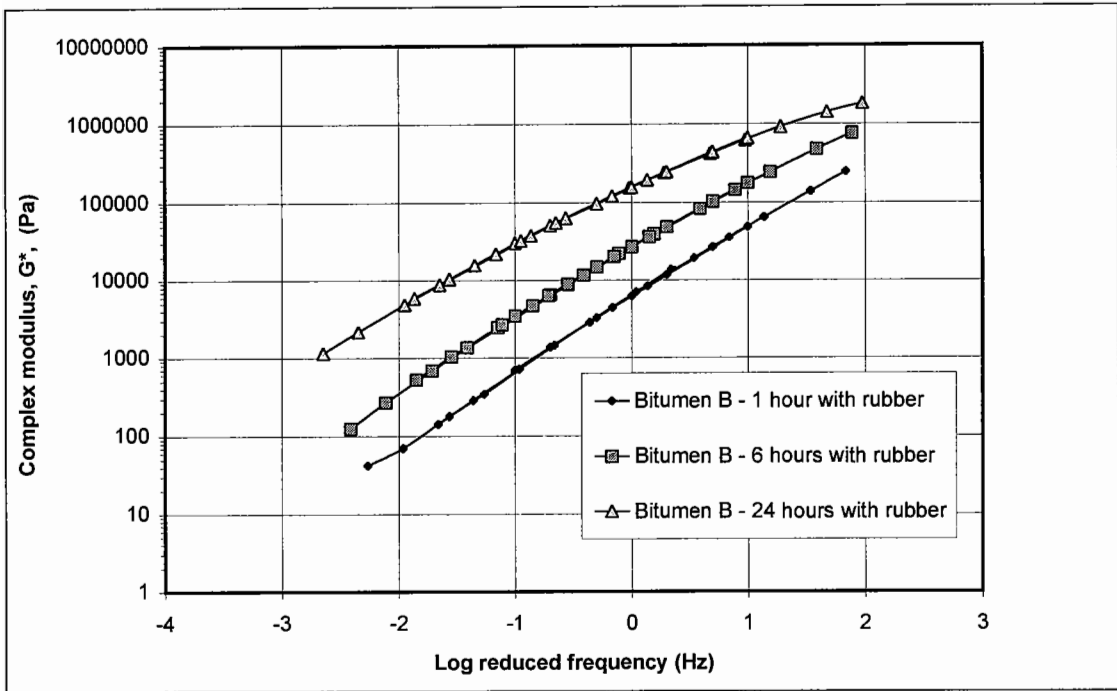


Figure 4.25 - Master curves of complex modulus at a reference temperature of 45°C for 100 Pen Bitumen B cured with rubber for 1, 6 and 24 hours at 155°C

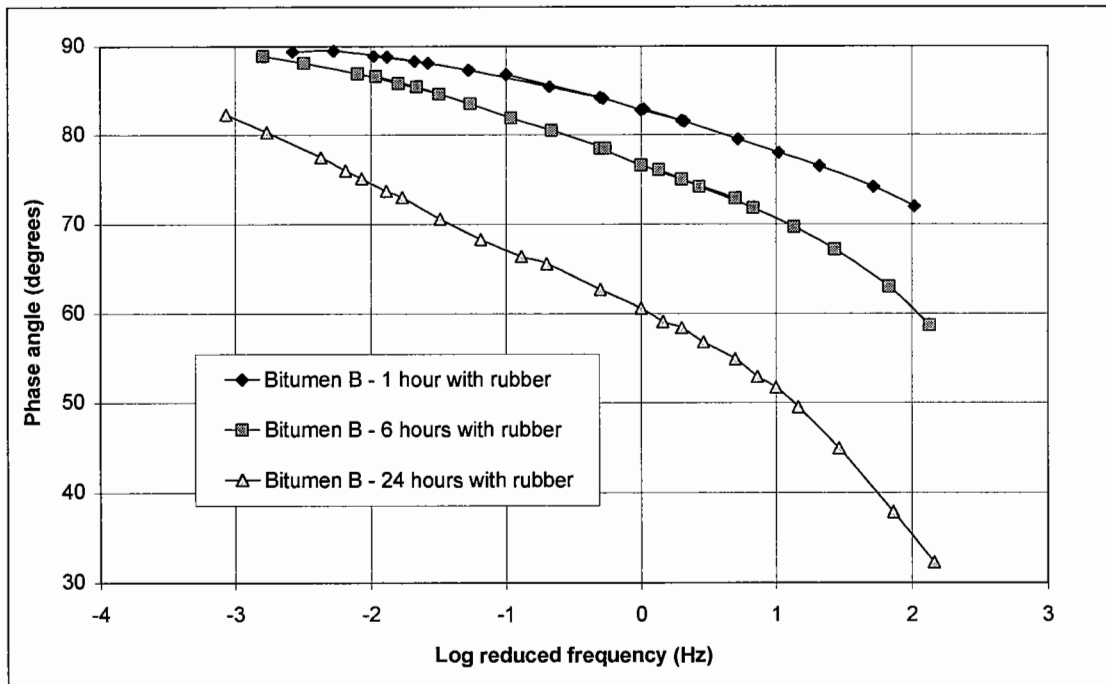


Figure 4.26 - Master curves of phase angle at a reference temperature of 45°C for 100 Pen Bitumen B cured with rubber for 1, 6 and 24 hours at 155°C

The master curves for Bitumen B aged without rubber are presented in Figures 4.23 and 4.24. The results for the same bitumen aged with 33% rubber are presented in Figures 4.25 and 4.26.

The results show the same trend as the Bitumen A. Curing without rubber shows a slight increase in the complex modulus and a small decrease in the phase angle. The addition of rubber causes greater changes in these rheological values. The effects of the rubber on the properties of the Bitumen B are much greater than Bitumen A. The complex modulus is increased by a factor of 25 at a loading frequency of 1Hz when aged for 24 hours in rubber which is considerably higher than the factor of 2.8 measured for Bitumen A. The phase angle for Bitumen B also shows a much greater decrease; from 78° to 51° at 1 Hz for 24 hours, whereas the Bitumen A changed from 87° to 81° . The differences could be attributable to the larger proportion of asphaltene content in Bitumen B.

4.4.4 Cohesion Testing

The samples of residual bitumen collected from the curing tests were tested in the Vialit Pendulum Cohesion test. Figure 4.27 given below shows two cohesion curves from Bitumen A, one cured for 1 hour without rubber and 1 cured for 6 hours in rubber. The curves indicate a maximum cohesion value for each curve at a temperature of approximately 50°C . These values can be used as comparisons between the different residual bitumens.

Figure 4.28 shows a summary of the maximum cohesion values the two bitumens under different curing regimes. The results suggest that there was no significant change in the cohesion of Bitumen A throughout the curing period with rubber. However, there is a significant drop in the maximum cohesion value of the residual Bitumen B after 24 hours curing.

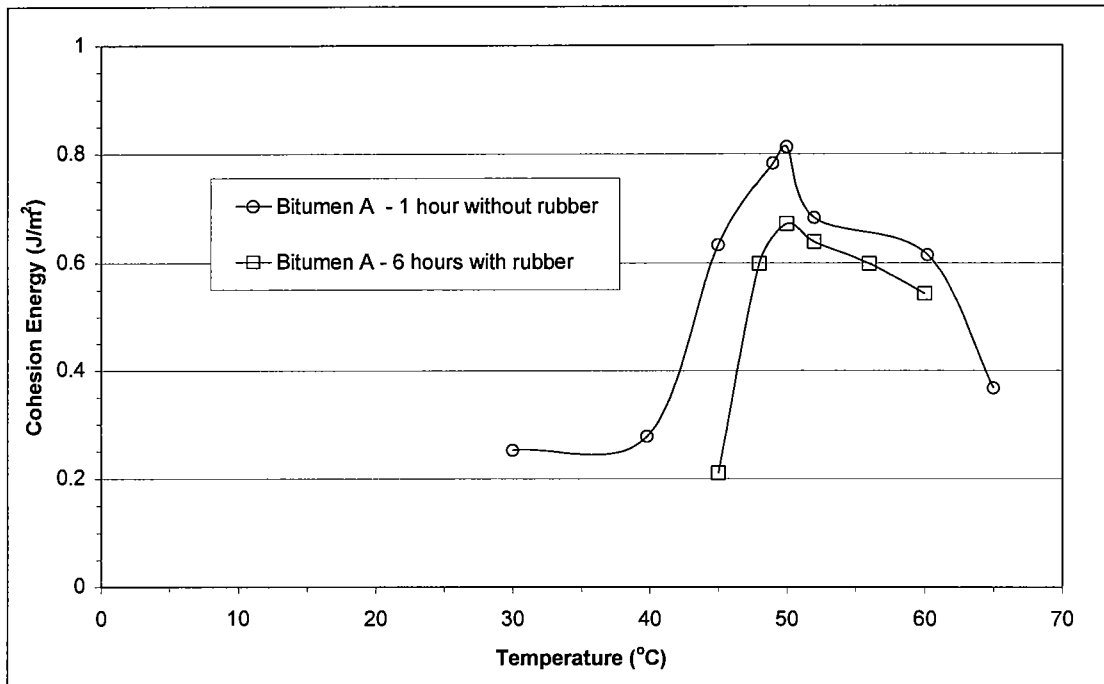


Figure 4.26 - Vialit Pendulum Cohesion curves for Bitumen A cured for different periods

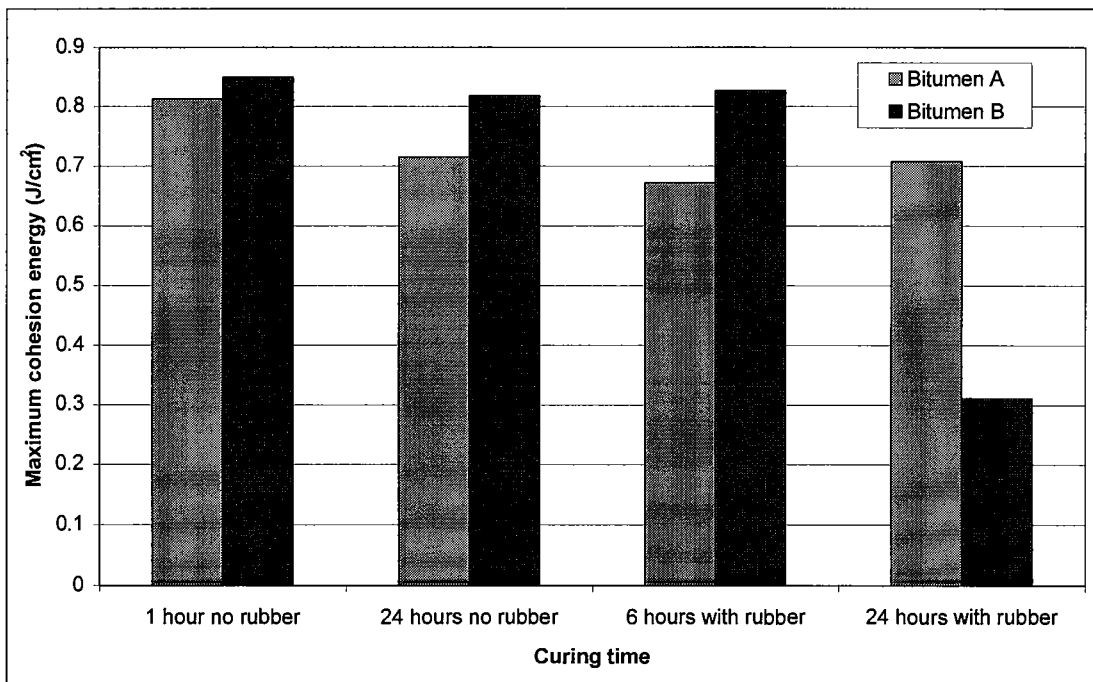


Figure 4.28 - Summary of maximum cohesion values of the Bitumens A and B cured for different periods

4.4.5 Discussion

The laboratory investigation has determined the absorption of bitumen solvent by crumb rubber when held at elevated temperatures (155°C). The composition of the bitumen is altered through the interaction with the rubber, suggesting that certain fractions of the bitumen are more readily absorbed than others. This change in composition is altering the rheological properties and cohesion of the residual bitumen. The degree of change in mechanical properties appears to be affected by the composition of the bitumen. The change in mechanical properties of Bitumen A, which has a high aromatic content is not as great as Bitumen B, which has a high asphaltene content. Therefore, Bitumen A is more compatible as a binder with crumb rubber as its mechanical properties are less susceptible to change.

The phenomenon of polymer swelling in bitumen is used when blending polymer modified bitumens. A polymer modified bitumen consists of bitumen and a specially prepared polymer such as styrene-butadiene-styrene (SBS) or ethylene vinyl acetate (EVA). The polymer is added to the bitumen and allowed to blend at high temperatures. The blending involves the polymer structure absorbing fractions of the bitumen, expanding and forming a finely dispersed polymer network within the bitumen. The composition of the bitumen is vital to achieving a good blend and generally the critical factor is the phase of dispersion in the bitumen. A parameter used to characterise the state of dispersion of bitumen is the colloidal instability index (CI) and is defined as follows:

$$CI = \frac{\text{asphaltenes} + \text{saturates}}{\text{resins} + \text{aromatics}} \quad 4.3$$

A bitumen with a low colloidal index would indicate that the asphaltenes are peptised in an oil based medium. Loeber *et al.* [1996] reported, on a study of the addition of EVA copolymers into several bitumens, that a low colloidal index leads to a finely dispersed structure that exhibits a high cohesive energy. Conversely a high colloidal index leads to a heterogeneous structure with a low cohesive energy. The best rheological performance of the polymer modified bitumens (PmB) was obtained with a colloidal index of the bitumen of 0.3. Above this value, the performance of the PmB

was reduced. Therefore, the colloidal index can be used to determine the compatibility of a bitumen to produce a good polymer modified bitumen. Although the crumb rubber is not dissolved in the bitumen a similar comparison could be made to determine the compatibility of a bitumen with crumb rubber in the dry process.

Table 4.1 presents a comparison between the colloidal index of the cured bitumens with their measured performance. The values in brackets represent the normalised figures with the original properties.

Table 4.1 - Summary of the properties of the two residual bitumens after curing

Bitumen	CI	Max. Cohesion (J/cm ²)	Complex modulus @ 1 Hz, 45°C (Pa)	Phase angle @ 1 Hz, 45°C (degrees)
Bitumen A - 1 hour no rubber	0.16 (1.0)	0.80 (1.0)	4600 (1.0)	88.8 (1.0)
Bitumen A - 6 hours no rubber	0.17 (1.06)	-	5100 (1.11)	88.7 (1.0)
Bitumen A - 24 hours no rubber	0.17 (1.06)	0.71 (0.89)	6600 (1.43)	88.6 (1.0)
Bitumen A - 1 hour with rubber	0.17 (1.06)	-	5200 (1.13)	88.7 (1.0)
Bitumen A - 6 hours with rubber	0.17 (1.06)	0.70 (0.88)	7130 (1.55)	88.3 (0.99)
Bitumen A - 24 hours with rubber	0.2 (1.25)	0.75 (0.94)	14450 (3.14)	86.5 (0.97)
Bitumen B - 1 hour no rubber	0.45 (1.0)	0.85 (1.0)	6100 (1.0)	83.4 (1.0)
Bitumen B - 6 hours no rubber	0.46 (1.02)	-	6600 (1.08)	82.8 (0.99)
Bitumen B - 24 hours no rubber	0.44 (0.98)	0.82 (0.96)	8750 (1.43)	81.2 (0.97)
Bitumen B - 1 hour with rubber	0.49 (1.09)	-	6250 (1.02)	82.8 (0.99)
Bitumen B - 6 hours with rubber	0.50 (1.11)	0.85 (1.0)	29000 (4.75)	76.6 (0.92)
Bitumen B - 24 hours with rubber	0.59 (1.31)	0.30 (0.35)	156000 (25.6)	60.6 (0.73)

The table illustrates the large changes in mechanical properties of Bitumen B compared to Bitumen A when cured in rubber. It also shows that Bitumen B has a greater colloidal instability index than the Bitumen A. This may indicate that the properties of Bitumen B are affected more through the interaction with the crumb

rubber because it has a smaller degree of dispersion, shown by a high colloidal instability index. The greater changes in colloidal instability index illustrate that the rubber is changing the colloidal structure of Bitumen B more, resulting in greater changes in the rheological and cohesive values.

4.4.6 Summary

This study has showed that when crumb rubber is added to a bituminous mixture to impart elastomeric inclusions into the matrix it can absorb fractions of the bitumen when held at elevated temperatures. Based on the data collected from this study, the following conclusions are warranted:

- The composition of bitumen does not appear to alter the rate of interaction between the rubber and the bitumen
- In addition to the oxidation of the bitumen, the residual bitumen constitution changes through the interaction with the crumb rubber, suggesting the rubber absorbs mostly saturates and aromatics.
- In addition to the oxidation of the bitumen, the rheological properties of the residual bitumen change leading to;
 - an increase in stiffness
 - a decrease in phase angle, tending towards a more elastic response
- A large change in the colloidal instability index appears to relate to a large change in the rheological properties of the bitumen.
- A low colloidal instability index (<0.3) results in a bitumen that when cured with crumb rubber does not have a large change in mechanical properties, suggesting that it is more compatible.

These findings show that the composition of the two bitumens used has no significant effect on the rate of interaction, but does have an effect on the properties of the residual bitumen. This may suggest that the effect of the interaction on the properties of a bituminous material with rubber aggregate can be reduced by choosing a bitumen with a low colloidal stability index.

This work has confirmed that the rubber is absorbing the lighter molecular weight fractions of the bitumen. Since the lighter fractions in the SBS bitumen support the SBS polymer to form a finely dispersed phase, it is likely that the SBS structure is becoming diminished through the interaction with the rubber. The bitumen in the SBS PmB is becoming incompatible with the polymer because its colloidal structure and bitumen constitution is changing.

4.5 Changes in mechanical performance of rubber

Work has been carried out by an undergraduate under the supervision of the author to investigate the effect of the rubber-bitumen interaction on the mechanical performance of the rubber. Samples of rubber were prepared that could be used to measure the uni-axial stiffness of the rubber. The aim was to measure the stiffness of samples before and after treatment with bitumen so that the effect of the rubber swelling could be seen.

A test rig was developed to measure the uni-axial stiffness of a cylindrical specimen of rubber. The specimens were collected from the walls of truck tyres, as this provided the thickest specimen possible. The specimens measured 20mm diameter by 5-6mm thick representing a very low radius to thickness aspect ratio. This is not ideal for uni-axial testing because the transverse friction between the loading plates and the rubber will influence the response of the rubber sample under compressive loading. The specimens were compressed through their thickness and the response measured by LVDT's. A schematic is provided in Figure 4.29.

4.5.1 Method

All the cylindrical samples of rubber were collected from the apex of the same truck tyre by using a coring drill so that the type of rubber was consistent.

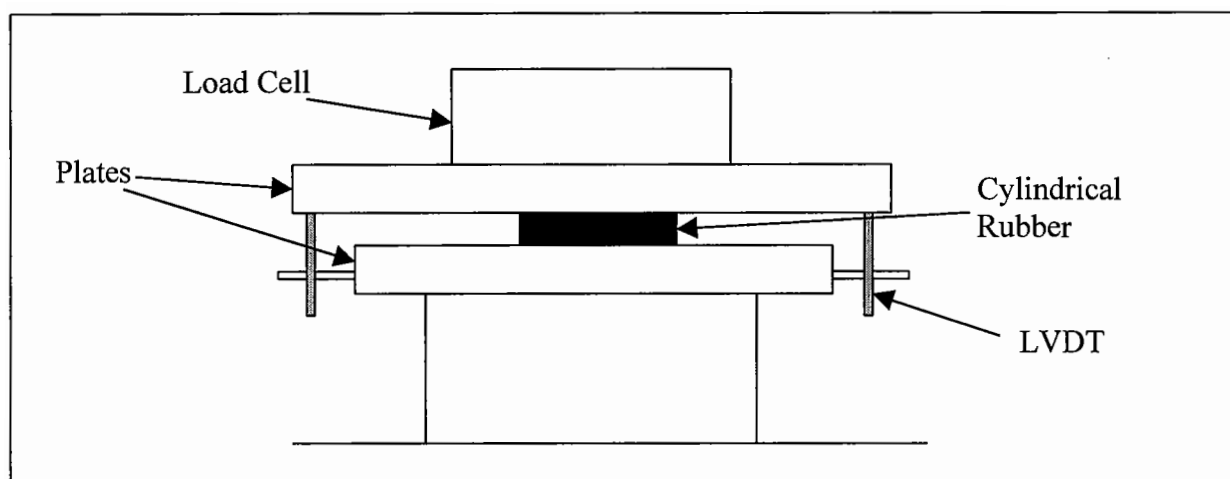


Figure 4.29 - A schematic of the uni-axial apparatus used to test the stiffness response of cylindrical samples of truck tyre rubber

The samples were all tested prior to treatment with bitumen by dynamic sinusoidal loading under strain control at 2 different frequencies 2 and 10Hz at 20°C. The samples were then split into two groups of three. One set was soaked in bitumen at 185°C for 1 hour and the second group was soaked at the same temperature for 24 hours. All the samples were soaked on a wire frame in individual beakers with a mass of bitumen 8 times the mass of the rubber sample. The samples soaked in bitumen for 1 hour increased in mass by 6%. The samples left in bitumen for 24 hours increase in mass by 36%.

After treatment the samples were tested in the uni-axial apparatus under the same conditions as pre-treatment so that the results could be compared.

4.5.2 Results

The test was used to measure the uni-axial stiffness by calculating the vertical strain response due to a stress applied to the sample. The phase angle was also measured by calculating the time difference between the applied stress and the response of the strain. To reduce the effect of the friction between the loading plates and rubber samples a silicon lubricant was sprayed onto the plates. This reduced the influence of the friction on the uni-axial stiffness of the rubber sample. The average results for the testing are given in Table 4.2.

Table 4.2 -Summary of Results from uni-axial testing of cylindrical rubber specimens

Sample	2Hz				10Hz			
	Loading Stiffness (MPa)		Phase Angle (degrees)		Loading Stiffness (MPa)		Phase Angle (degrees)	
	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
Rubber - untreated	8.35	0.23	17.5	2.8	9.23	0.3	26.8	5.1
Rubber -treated in SBS bitumen for 1 hour	4.58	0.30	15.5	1.4	4.39	0.13	18.1	2.2
Rubber - treated in SBS bitumen for 24 hours*	4.67	0.11	19.4	2.7	5.28	0.05	21.8	2.8

* Mean taken from a sample set of two

The results cannot be conclusive because of the small number of samples used. However, the standard deviations were calculated from 5 repeated tests on each sample so the results provide an indication of how the addition of bitumen affects the mechanical performance of the rubber.

4.5.3 Summary

The general conclusion is that the rubber-bitumen system has a lower stiffness than the rubber system alone. There is some evidence to suggest that the rubber may actually gets slightly stiffer the longer it is left in the bitumen. The results also suggest that the phase angle is lower for the rubber-bitumen system. This would suggest that the rubber-bitumen is more elastic than the rubber alone. Both of these findings confirm the research by Flory et al. Pt I (1943) mentioned in the literature review that concluded that diffusion of solvents into would soften the rubber but increase its elasticity.

4.6 Conclusions

The work described in the last 2 chapters has shown that there is an interaction between the rubber and the bitumen at high temperatures. The rubber is absorbing the lighter fractions of the bitumen and swelling. The mechanical performance of the

residual bitumen is affected because the bitumen composition is changing due to the lighter fractions being absorbed.

The SBS PmB has been tested and has been shown to diffuse into the rubber. This is affecting the performance of the bitumen and the polymer because the balance of the bitumen constituents is changing and causing the bitumen to be less compatible with the SBS. It is difficult to decide what is actually happening to the SBS structure within the bitumen as the lighter fraction is absorbed. However, curing tests show that the influence of the SBS is diminished through ageing, suggesting that the extent of SBS structure is reduced through the loss of the lighter fraction which acts as a supporting medium. Essentially, the network structure of the SBS breaks up because the residual bitumen can no longer support it. This is shown in the curing tests when after the reaction one can observe lumps of SBS on the surface of the bitumen. This could suggest the SBS is precipitating out of the bitumen after it has reacted with the crumb rubber because the blend is no longer compatible.

The interaction between the rubber and the penetration grade bitumens has enabled a more detailed look at the change in bitumen composition. This has confirmed that the crumb rubber is absorbing mainly the aromatic and saturate fractions of the bitumen and changing the rheological properties of the bitumen.

5. DURABILITY OF PLAYGROUND SURFACES

5.1 Introduction

IAA has a number of different uses; the two main areas are playground surfaces and the shock-pad layer of artificial sports turf pitches. The shock-pad layer for an artificial sports turf pitch is laid upon a sub base material and then covered by a sanded carpet. Therefore, it is not a surface layer and is not as susceptible to weathering and mechanical wear. The playground surface is designed to be a surface layer and to provide impact absorption characteristics direct to the user rather than through a carpet. Therefore, this material is more susceptible to weathering and mechanical wear and this chapter will investigate the durability of IAA as a playground surface.

Initial in-situ trials of IAA have performed poorly due to the material matrix breaking up under use, leaving particles of rubber and aggregate loose on the surface. The reason for this failure is due to two main factors; the rubber is absorbing proportions of the bitumen and the material is flexible. The flexibility of the material allows greater movement of the rubber and aggregate particles in the mixture when loaded which can cause the binder to fracture due to its lack of flexibility.

The first section will define mechanical durability and then review existing methods for testing the mechanical durability of surface materials, both bituminous and non-bituminous. A summary of the initial in-situ investigations carried out on the durability of IAA will illustrate a need for a new kind of test that measures the mechanical durability of the surface material.

A new test to measure the mechanical durability was developed at the University of Nottingham called the Abrasive Wear Test. Results are related to the cohesive/adhesive strength of the material matrix of IAA and the development of the test will be outlined.

5.2 Mechanical Durability

The general definition of durability is the ability of a material or substance to exist for a long period of time without significant deterioration (Scholz, 1995). The deterioration factors can be classified in two main groups, environmental and mechanical. The environmental factors include ageing, temperature, water and radiation from the sun (Scholz, 1995). The mechanical factors involve loading the material in a way that reduces its ability to exist, such as abrading or tearing.

Surface materials are affected by both factors of deterioration. The action of the environment, such as temperature changes, rain water, oxidation and radiation from the sun can all cause a reduction in the materials performance and thus reduce its durability. The action of loading of a surface material can reduce the durability of the material by mechanically wearing the material away. The ability of the material to resist this physical deterioration is to be termed mechanical durability for the purposes of this literature. Mechanical durability is seen as the main cause of failure of the initial in-situ trials of IAA and is to be investigated in this and the subsequent chapter.

5.2.1 Bituminous Materials

The mechanical durability of bituminous road materials is applicable to the surface where the action of traffic loading can wear the material away. A bituminous road material is a mixture of aggregate and bitumen. The aggregate particles of different sizes (usually a maximum of 20mm) are bound together by the bitumen. The two basic mechanisms of mechanical wear can be identified as either abrading of the material into finer particles (Type 1) or breaking the bitumen bond leaving the original aggregate particles intact (Type 2). The Type 1 failure mechanism is a function of the abrasive resistance of the bitumen and aggregates and is known to reduce the texture depth and the skid resistance of the surface. Type 2 involves deterioration of the cohesive and adhesive strength of the bitumen allowing the aggregate particles to work free. The two mechanisms are shown schematically in Figure 5.1. Cohesive strength is the ability of the binder to bind to itself, whereas adhesive strength is the ability of a material to bind to another substance. The 'plucking' out of the aggregate particles can be a measure of both the cohesive and the

adhesive strength of the binder, dependant on which is the lowest in a particular situation. A cohesive failure of the material would leave the loose aggregate particles still coated in bitumen because the bitumen-bitumen bond will have been broken. An adhesive failure would leave a clean face on the aggregate particle because the aggregate-bitumen bond will have been broken. These definitions are simplified because in reality the type of failure is difficult to assess but both relate to the performance of the binder in the bituminous pavement mixture. Damage to the aggregate would indicate the bitumen is performing well as a binder and the aggregate has the lowest mechanical durability.

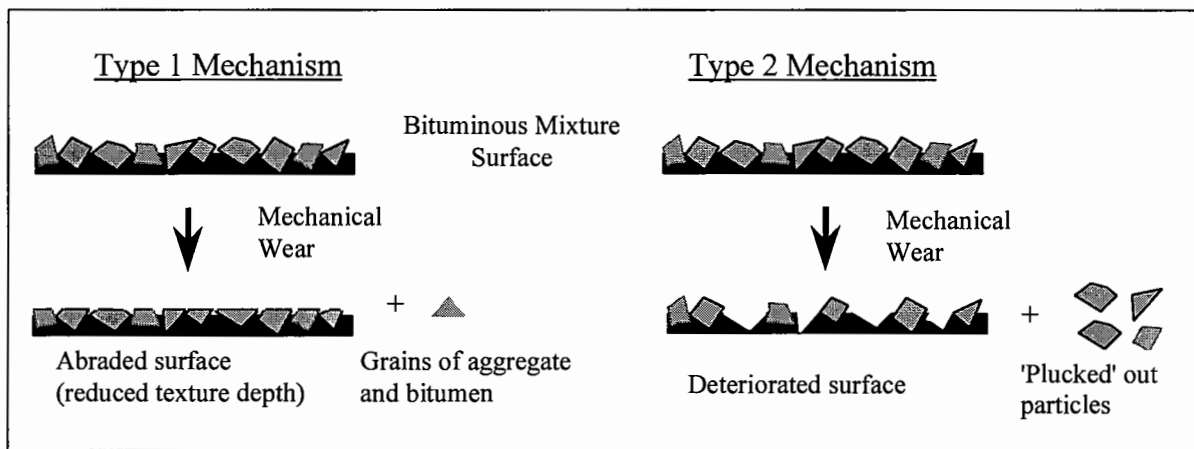


Figure 5.1 - Failure mechanisms of bituminous surface materials through mechanical durability

The nature of most types of bituminous pavements and their uses dictate that the major failure mode is cracking or rutting due to vertical wheel loading. The main mode of failure from mechanical wear is Type 1, where the texture depth and skid resistance of the pavement is reduced. The action of material loss through poor adhesion/cohesion is not a critical failure mechanism and as such, not many tests have been developed to assess this property. However, one test that was developed to assess the ability of the bituminous material to bind together is the Cantabro test. The Cantabro test uses a specimen prepared in a Marshall mould and rotates it in a Los Angeles rattler (without ball bearings), which is a large drum, for 300 rotations. The mass loss of the main sample when the test is finished is used as an indication of the performance of the material. Its primary measurement is the resistance of the material to disintegration (Woodside et al., 1997).

The Cantabro test was originally developed at the University of Cantabria in Spain. It has been used as a tool for porous asphalt mixture evaluation. Perez-Jimenez et al.

(1989) used the test to assess the difference in mechanical durability due to the action of water on bituminous material. They discovered that the water reduced the structural stability of the material, essentially causing it to disintegrate. The result is attributable to water causing a reduction in the adhesive bond between the bitumen and the aggregate. The failure of the bond between the bitumen and the aggregate is regarded as stripping and is thought to be caused by moisture having a greater affinity than bitumen to the aggregate and therefore rupturing the bond between the aggregate and the bitumen (Kennedy, 1985 and Terrel, 1989). Perez-Jimenez et al. (1990) used the test to evaluate the performance of porous asphalt mixtures made with polymer modified binders, by assessing the resistance to disintegration.

The advantages of the Cantabro test are that it is a simple test, easy to carry out and provides quick results. However, it is a crude test and there is a question over what it actually measures. The failure mechanisms induced are caused by an unnatural loading regime, (i.e. tumbling a sample of material) therefore it is difficult to ascertain what is actually happening to the material when it is breaking up. It is not possible to define whether it is a failure of the bitumen-aggregate bond, the bitumen-bitumen bond or the break up of the aggregate. The test is not simulative of the loading that a playground surface is usually subjected to and is therefore felt to be unsuitable to assess the mechanical durability of IAA.

Another test developed for bituminous road materials is the Scuffing Test. The Scuffing Test is designed to measure the resistance of a high friction surface road material to wear. The test procedure is to pass a loaded pneumatic tyre, which is set at an angle to motion, over the surface of a specimen held at an elevated temperature (BS 598, 1987). The pneumatic tyre is loaded perpendicular to the movement to provide a normal load on the specimen. The wheel is repeatedly passed over the specimen 500 times and the loss in texture depth and loss of skid resistance are measured.

This test is more simulative of the loading regimes for bituminous road surfaces when cars and trucks are stopping, starting or turning. It provides a measure of the resistance of the aggregate and bitumen in the mixture to abrasion, thus reducing the texture depth and the skid resistance through a Type 1 mechanism of failure. It does

not appear to be a measure of the adhesive/cohesive strength of the bitumen in the mixture. Although this test is more simulative of loading in the road pavement, it does not represent the typical loading on a playground surface.

A further measure of mechanical durability of bituminous materials is in simulating the wear of studded tyres. This is particularly a concern in Scandinavian countries, Canada, USA and other countries with cold climates where vehicles need extra grip in snowy and icy conditions. Considerable work has been carried out simulating and measuring the wear that is sustained by the road due to the use of studded tyres. Cantz (1972) developed a laboratory test to compare the performance of different bituminous and cement based materials on wear due to a single metal stud that is normally found in a studded tyre. This test involved placing a normal load on a surface through the single metal stud, then moving the surface laterally underneath the stud. Measuring the mass lost from the surface material after a set number of passes assessed the performance of the material. Keyser, (1979) developed a more simulative test by moving a wheel with a studded tyre over a surface in a circle. This was called a traffic simulator and the rut depth generated after a number of rotations was used as a measure of the performance of the surface material.

The failure mechanism reported for both of these tests was a mixture of both Type 1 and Type 2, where the studs mainly abraded the aggregate, occasionally plucking out whole particles. Therefore, both the aggregate quality and the cohesive/adhesive properties of the bitumen were a factor in the resistance of the material to studded tyre wear.

Summary

The four tests described are not simulative of the loading regime of a playground because they were developed for bituminous road materials. The Cantabro test does not simulate any specific loading regime and is felt unsuitable to evaluate the mechanical durability of a playground surface. The Scuffing Test is specifically designed for the action of tyres on the road surface and simulates a Type 1 failure mechanism. The intention is to use a test that imparts a Type 2 mechanism of failure

and the tests designed to simulate studded tyre wear produce both types of failure making them unsuitable for IAA.

5.2.2 Sports and Safety Surfaces

To fully understand the loading a playground surface is subjected to, the interaction between a person and a surface needs to be considered. An area where this interaction is simulated is through the testing of the mechanical durability of sports surfaces.

There are three basic tests outlined in BS 7044 Section 2.3, that are designed to measure the mechanical durability of a sports surface material and are utilised as standards by some sporting bodies. Method 1 is a test of abrasive resistance of a specimen to the action of spinning wheels used by the International Tennis Federation. The second test method is the abrasion of a specimen by the action of rotating metal blades used by the International Hockey Federation and the third is a test to determine the resistance of the surface to spikes.

In Method 1, a pair of abrasive wheels are placed on the surface of the specimen and rotated over the same spot for set increments. It is designed for all artificial sports surfaces apart from artificial turf. After each increment, the loose material from the specimen is removed and weighed. This is repeated for a set number of increments and the mass loss per increment is recorded. The problem associated with this are that the rubber wheels can become loaded with debris and therefore the abrasive work done by the wheels is altered. It is also not a loading mechanism commonly found on sports or safety surfaces.

The second method of measuring the abrasive resistance of a surface to rotating blades represents a more simulative method of loading. This is specific to non-sand filled artificial turf and involves a circular test piece rotating at the same speed and direction as a circular abrading tool, but with the axes of rotation offset. The abrading tool is a row of metal blades on a circular base as shown in Figure 5.2.

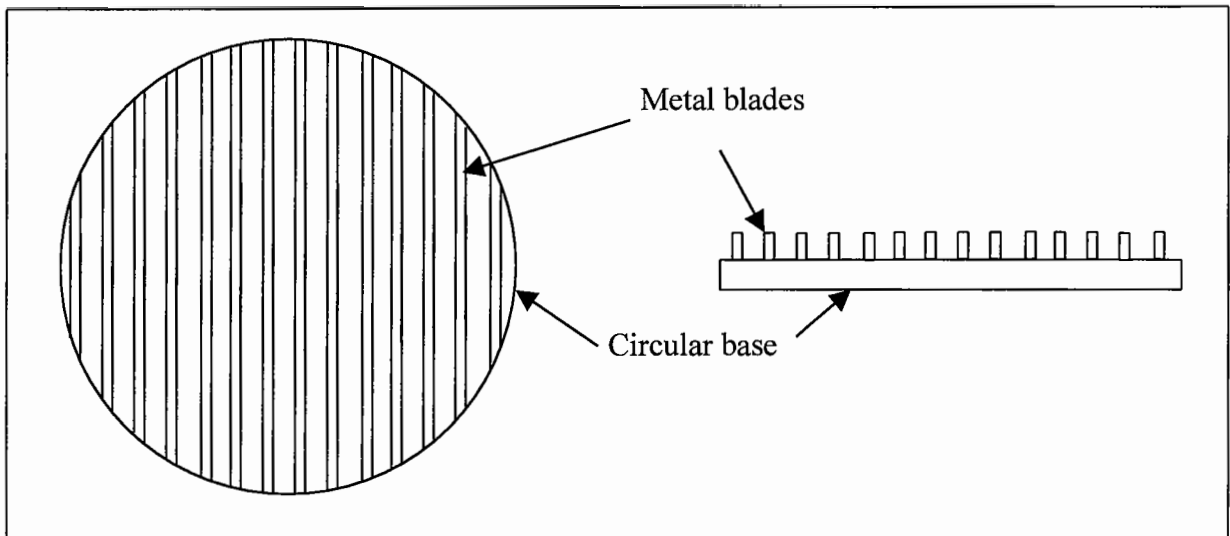


Figure 5.2 - Schematic of the abrading tool used for measuring the resistance to wear from metal blades (BS 7044, 1990)

The abrading tool acts under a load of 2kg. The test is carried out at defined increments and then the loose material is removed and weighed each time. This test is more simulative of the twisting and turning of a foot on the surface. However, the load applied through the abrading tool to the surface is only 2kg relating to an abrading pressure on the material of 55kPa. In comparison, the contact pressure from the front part of a foot (in contact when a person turns), assuming a flat contact, applies a contact pressure of approximately 120kPa through an average sized male (75kg).

The last two methods have utilised a flat specimen and rated the resistance to abrading by the loss of loose particles. The third method given in BS 7044 relates specifically to running tracks where the action of the spikes from running shoes can severely deteriorate the surface material. This test involves fixing the specimen to the inside of a drum, a tetrahedron with spikes on each corner is then placed inside and the drum is rotated for a predetermined period. The action of the spikes on the specimen causes surface damage which is inspected and then ranked using a scale. This test is only specific to running tracks and does not simulate the deterioration mechanisms of a playground.

The first two methods described in this section both apply abrasion in increments. After each increment, the loose material is removed and the remaining specimen is abraded again. There is a lack of simulation using this method because if the material is in-situ and is abraded through use, the loose material will not necessarily be removed. The action of movement of the loose material over the remaining surface would be expected to accelerate the further loss of material. Therefore, a more simulative test would leave the loose material on the surface after each increment.

5.3 Development of the Abrasive Wear Test

The previous section described existing tests for measuring the resistance to mechanical durability of a surface material. The tests for bituminous materials are not simulative of the interaction between the foot and the surface that a playground would undergo. The tests for artificial sports surfaces are more suited to a homogenous material, unlike IAA, where the principle failure due to abrasive wear is the 'plucking' of particles. Therefore, it seems apparent that a test must be developed to abrade the surface of IAA, to simulate the interaction between foot and surface and 'pluck' out the particles and thus measure the adhesive/cohesive properties of the bitumen in the IAA mixture. This will provide a quantitative measure of the mechanical durability of the IAA material as a playground surface. The main aim is to use an abrasive wear test to assess what conditions reduce the ability of the material to bind together and perform as a playground surface for its design life.

5.3.1 Design Criteria

The criteria for the abrasive wear test for IAA, were to measure the abrasive resistance of the material to a Type 2 failure (outlined in Section 5.2.1). The test also had to be simulative of an expected loading regime for a playground, to help assess the practical capabilities. The following list contains the factors considered when designing the abrasive wear test.

- 1) Apply a Type 2 mode of failure to the surface
- 2) Apply a realistic load/pressure
- 3) Realistic conditions (i.e temperature, loading time)

- 4) Repeatable
- 5) Utilises both laboratory and in-situ prepared samples
- 6) Not dependant on thickness of sample
- 7) Easy to use

5.3.2 Abrasive Wear Test Mk I

The first protocol for the abrasive wear test was based around applying a twisting load to simulate the turning, stopping and starting of a person moving on the surface. An abrading tool was designed to represent the ball and toes of the foot that are in contact with the surface during these movements. The tool also had to be re-useable, so it was designed using steel instead of rubber which would have been more simulative for a shoe sole, but would have worn through testing. This also meant that the abraded material did not contain fragments of the abrading tool. The face of the abrading tool was a grid arranged array of pyramid shaped studs each 5mm deep. Figure 5.3 illustrates the first prototype and Figure 5.4 shows the arrangement of the studs on the face of the abrasive tool.

A normal load of 1kN was applied through the abrading tool to represent the loading of a man moving on the surface (an average sized man would impose 750N when balanced on one foot). The abrading tool was rotated through an arc of 60° by a loading ram moving transversely to the normal load.

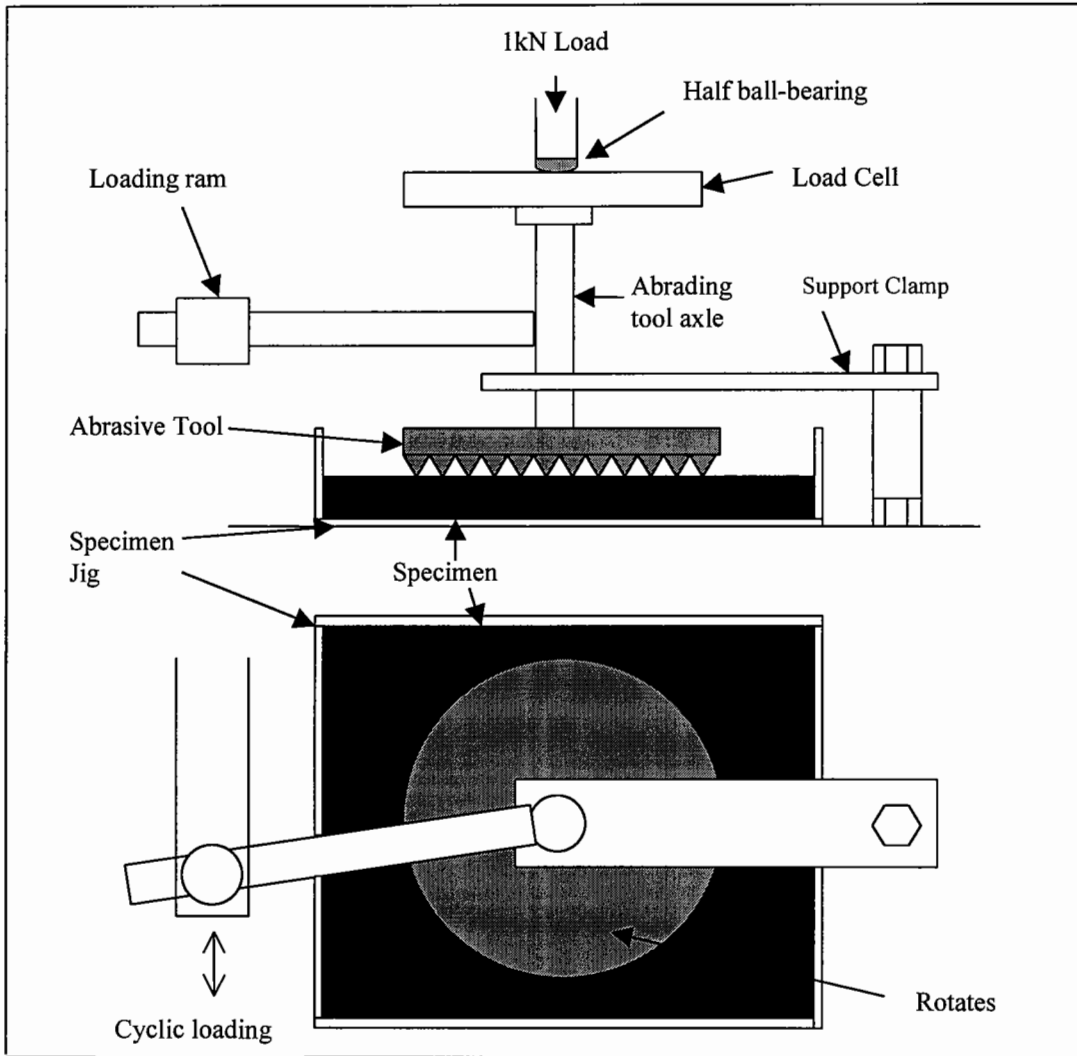


Figure 5.3 - Schematic of Abrasive Wear Test Mk I

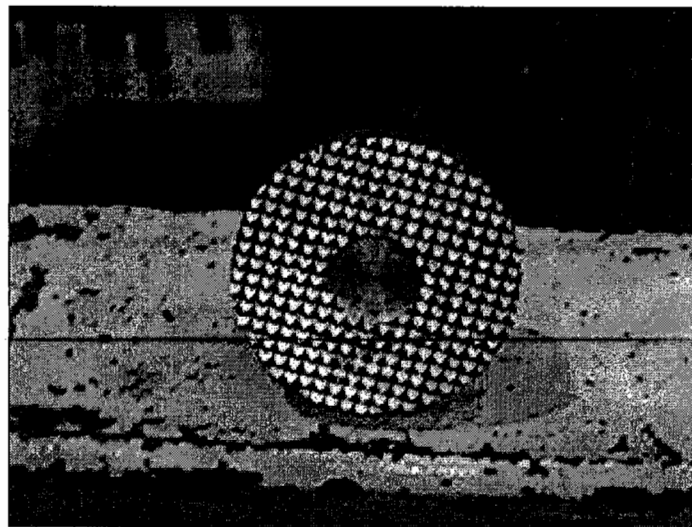


Figure 5.4 - Picture of the face of the abrading tool used in the Abrasive Wear Test

Before the test started, the specimen was weighed, it was then placed in the jig and a normal load of 1kN was placed on it through the abrading tool. The test was then started and the abrading tool was rotated through its 60° arc 100 times. The specimen was then removed and the loose particles were removed and weighed. The mass loss was recorded and the percentage mass loss of the available mass was calculated.

5.3.3 Preliminary Repeatability Study, Mk I

A repeatability study was carried out using the Abrasive Wear Test Mk I to assess the variability of the test. Initially, 5 slabs of IAA 3/20 were made, from which 6 specimens could be taken to test in the rig. Each slab was made with the same batch details and under the same conditions. The mixture was not conditioned at mixing temperature prior to compaction, and will be referred to as unaged. The tests showed that the abrasive wear test was causing a Type 2 failure mechanism. The abrading tool 'plucked' out the aggregate and rubber particles whole, so the test was a measure of the ability of the bitumen to bind the aggregate and rubber together. There was no debris collecting on the abrading tool and the test was simple to carry out. However, the repeatability of the test was poor and the results for the study are summarised in Table 5.1.

Tables 5.1 - Summary of Abrasive Wear Test results on 3/20 IAA Unaged Samples using rig Mk I

Slab	No. of Samples	Average Mass Loss (g)	Average percentage mass loss	Standard deviation of percentage mass loss	Ratio of Standard deviation and average mass loss
1	6	4.8	2.12%	1.22%	0.58
2	6	5.17	2.28%	0.76%	0.33
3	6	3.83	1.69%	0.52%	0.31
4	6	2.17	0.95%	0.43%	0.45
5	6	1.5	0.66%	0.24%	0.36
Total averages	30	3.44	1.52%	0.91%	0.41

The average percentage mass loss varies between each slab quite considerably between 0.66% up to 2.28%. This would normally indicate that the variability in results was due to inconsistent production of the slabs. However, the variability of the

mass loss within each slab is very high, suggesting that the average values for each slab are not very accurate. Therefore, it is likely that the variability overall is due to the inconsistency of the test more than the material variability. The important figure to note is the high ratio of standard deviation to average percentage of mass loss. The variability of the test can be estimated by averaging the ratios of the five slabs. This gives an average ratio of 0.4, which can be characterised as the test variability.

The reason for the high variability of test results may be the small mass loss of the specimens. Therefore, knowing that ageing the material in the oven is reducing the mechanical durability of the material, three slabs were made that, between mixing and compaction, were held in a mixing temperature for 1 hour to simulate short term ageing. A similar repeatability study was carried out on these samples to see if the increased mass loss would reduce the test variability, the results are presented in Table 5.2.

Table 5.2 - Summary of Abrasive Wear Test results for 3/20 IAA aged for 1 hour using rig Mk I

Slab	No. of Samples	Average Mass Loss (g)	Average percentage mass loss	Standard deviation of percentage mass loss	Ratio of Standard deviation and average mass loss
1hr-1	6	10.7	4.7%	2.88%	0.61
1hr-2	6	10.2	4.48%	1.75%	0.39
1hr-3	6	5	2.2%	0.84%	0.38
Total Averages	18	8.61	3.8%	2.21%	0.46

These results have also shown a large standard deviation to mass loss ratio, indicating that the testing procedure must be changed if any worthwhile results are to be obtained from the test. The test variability ratio averages out at 0.46. Therefore, the primary factor that is producing large standard deviations from the test results is the mechanics and procedure of the test.

5.3.4 Discussion

The Mk I test rig applied the normal load through the abrading tool via a hydraulic actuator that was in contact with a half ball bearing on to a load cell placed above the abrading tool and the load was monitored throughout the test by the load cell. The load was set before the test commenced when the ram and abrading tool were stationary. When the test commenced and the arm was moving, there was a noticeable drop in the vertical load that was applied through the load cell. The drop was not consistent and varied within each test. The load also fluctuated as the ram moved backwards and forwards, suggesting that the load being applied was not completely normal to the specimen. It is worth noting that when the load measured was low, the mass loss for the test was also low. Therefore, this could be a factor in the high variability of the test mechanics and procedure.

The reason for the fluctuation was thought to be because the support is not holding the loading column vertical. As the ram moves it is applying a turning moment, to the column axis, causing the abrasive tool to tilt. This reduces the vertical load transferred to the sample because some of the load is transferred transversely. To reduce the turning moment being applied to the abrasive tool, a stronger support system was deemed necessary because the connection between the load actuator, half ball bearing and the load cell, was thought to be the main reason for the movement. To increase the support in this area, a different load cell was used that measured the load in series and could be connected solidly through the actuator, instead of being balanced by a half ball bearing. A steel sheath was also made and inserted over a shortened abrasive tool axle to support the top of the abrasive tool, reducing the tilting movement. Figure 5.5 illustrates the redesigned Mk II rig.

The same failure mechanism was achieved, but it was noticeable that the new rig caused a larger mass loss because the vertical load was maintained consistently. A repeatability study was carried out on the new rig to evaluate if the improvements had improved the test variability.

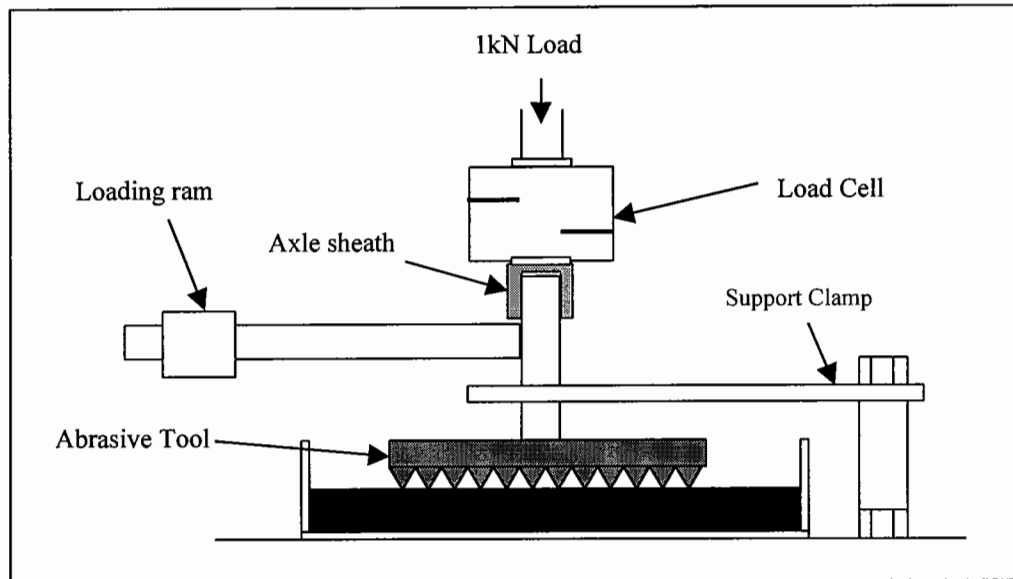


Figure 5.5 - Schematic of Abrasive Wear Test Mk II

5.3.5 Repeatability of Abrasive Wear Test, Mk II

The same repeatability procedure was carried out to assess the variability of the Mk II rig and the results are summarised in Table 5.3 for the unaged samples.

Table 5.3 - Summary of Abrasive Wear Test results on 3/20 IAA Unaged Samples in Mk II rig

Slab	Average Mass Loss	No. of Samples	Average percentage mass loss	Standard deviation of percentage mass loss	Ratio of Standard deviation and average mass loss
1	4	6	2.09%	0.17%	0.08
2	3.6	6	1.88%	0.13%	0.07
3	3.5	6	1.76%	0.24%	0.14
4	4.3	6	2.19%	0.06%	0.03
5	4	6	2.09%	0.2%	0.10
Total averages	3.9	30	2%	0.16%	0.08

These results show a marked improvement in the repeatability over the Mk I rig. The test variability has been reduced to give an average ratio of 0.08. The variability of the percentage mass loss between the 5 slabs has also been reduced considerably showing that the variability of mass loss between each slab was down to the test variability and

not the material variability. The increase lateral support for the abrasive tool axle and the load cell have reduced the tilting of the abrasive tool and thus increased the repeatability of the test.

5.4 Summary

This chapter has outlined the failure mechanisms associated with mechanical durability, in particular reference to failure of early trials of in-situ IAA. The failure mechanism for IAA has been defined as a Type 2 mechanism where the particles of aggregate and rubber are 'plucked' from the surface material. Existing test procedures have been analysed and it has been concluded from the literature review that there was not an existing test suitable for measuring and testing IAA for the defined failure mechanism. The development of the Abrasive Wear Test designed for measuring the mechanical durability of IAA has been described and a repeatability study was carried out to assess the variability. After some minor adjustments, the Abrasive Wear Test rig Mk II has been proved to be an accurate tool to measure the mechanical durability of IAA.

6. EFFECT OF RUBBER-BITUMEN INTERACTION ON MECHANICAL DURABILITY

Chapter 3 demonstrated that crumb rubber absorbs bitumen, especially when held at elevated temperatures and Chapter 4 has demonstrated the changes in the performance of the residual bitumen. The next stage is to quantify how this affects the performance of the material, particularly the mechanical durability which is the major failure mechanism when the material is used as a surface layer. The aim of this chapter is to investigate what factors affect the mechanical durability of the material and how it can be improved.

The rubber-bitumen interaction is most active at elevated temperatures. Therefore, the interaction will be extensive during the period when the material is at high temperatures. A short term ageing protocol was developed to simulate the period during which the mixture is held at mixing, transporting and laying (construction) temperatures (typically 155°C). Mixtures were aged for different periods, then compacted into slabs of material that were then tested for their mechanical durability in the abrasive wear test. Mixture designs were developed and short term ageing carried out to investigate what factors affect the mechanical durability of the material.

6.1 Short Term Ageing

Production of IAA is based on the production of conventional bituminous paving mixtures. A conventional batch mixing plant is used to produce IAA. The hot bituminous mixture is then transported via insulated trucks to the site where it is laid and compacted. The period from when the rubber comes into contact with the bitumen during mixing until it is laid and allowed to cool can be up to 6 hours. During this period the mixture is maintained at 155°C or above. Chapter 3 showed that the interaction between the rubber and the bitumen is considerable when held at elevated temperatures. Therefore, the interaction is the most active during the period when the material is mixed, transported and laid. Short term ageing refers to the simulation of this period when the material is held at elevated temperatures. Therefore, a protocol for short term ageing of the material in the laboratory was needed to model what is

happening to the material during production. To do this, the process of production must be assessed.

The batch mixing plant for bituminous materials is shown schematically in Figure 6.1.

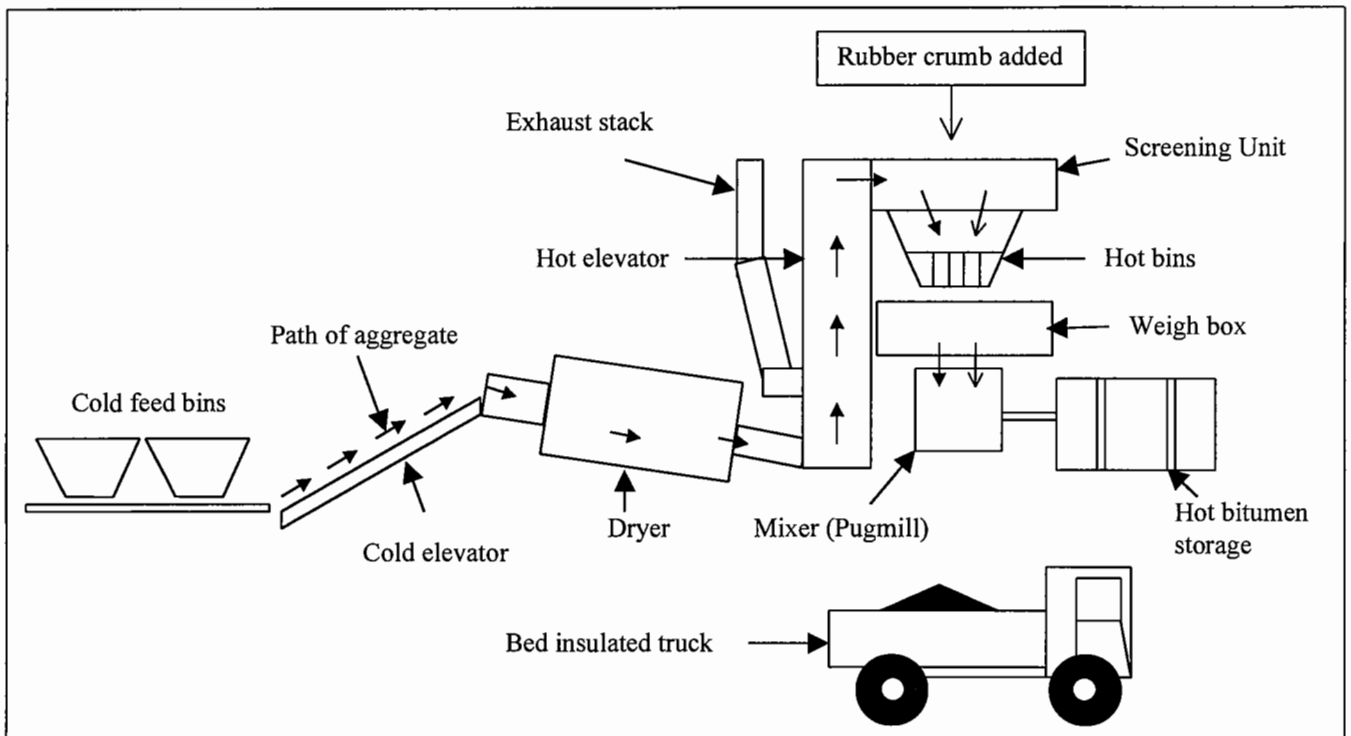


Figure 6.1 - Schematic of the Batch Mixing Process used for the production of IAA

In the process the aggregate is dried to remove moisture because moisture reduces the strength of bond between the aggregate and the bitumen. The hot aggregate (185°C) is then carried via a hot elevator to a screening unit, where the cold rubber is added. The screening unit groups the aggregate and rubber into the different gradings where they are then filtered into the hot bins and they are released into the weighing box. The weighing box is used to ensure the correct masses of each grade are added into the mixer to enable the batch to be an evenly graded mixture. The mixer or pugmill is an array of prongs on an axle that rotates as the hot bitumen is added. The bitumen is stored in a large heated tank and maintained at a temperature of 185°C . When the material has been mixed for 30 seconds, so that each particle is evenly coated, the batch is released into a truck with an insulated bed where upon it is transported to the site. When the material is placed in the truck, it is covered by a sheet to help maintain a temperature for the bulk of the material of approximately 155°C . This ensures that

when the material arrives on site it is workable and can be spread over the surface and compacted to achieve optimum density.

Simulation of this period of production is known as short term ageing. A protocol was developed at the University of Nottingham to short term age samples of IAA and is described below:

1. Weigh out correct mass of aggregate, rubber and bitumen as per mixture design sheet.
2. Heat aggregate batch to 185°C in a force draft oven and maintain for 1 hour.
3. Heat the SBS modified bitumen to 185°C in a force draft oven and maintain for 1 hour.
4. Place rubber in a heated mixer and add aggregate. Mix the two dry ingredients for about 30 seconds.
5. Add bitumen to the dry mixture and mix together for a further 30 seconds.
6. Measure the temperature of the mixture to ensure it is at 155°C.
7. Place mixture in a tray and place in a force draft oven at 155°C and leave for desired period of short term ageing.
8. After the mixture batch has been cured for the desired short term ageing time, remove the mixture from the oven and compact immediately.

The compacted specimen produced, once cooled, is then tested in the abrasive wear test and compared to unaged specimens to examine the affect of the short term ageing.

6.2 Mechanical Durability Testing

The short term ageing protocol was used to quantify the effect of the rubber-bitumen interaction on the mechanical durability of IAA by testing specimens in the abrasive wear test, described in Chapter 5.

6.2.1 Results for Original Mixture

Initially, the original IAA 3/20 mixture was used. This material consists of 15% by mass of 1-4mm rubber, 10% by mass of SBS modified bitumen and 75% by mass of

aggregate from 5mm to dust. Specimens were made that were short term aged at 0 (compacted after mixing), 3 and 6hrs and then tested in the abrasive wear test. The standard protocol of 1kN normal load for 100 twisting repetitions at 0.2Hz was applied. The percentage mass loss was calculated as a proportion of the mass directly underneath the abrasive tool. The results are presented in Figure 6.2.



Figure 6.2 - Percentage mass loss of short term aged specimens of the original 3/20 IAA tested in the Abrasive Wear Test

The results on Figure 6.2 contain 95% confidence limit error bars from a repeatability study carried out when developing the test by testing 20 identically produced specimens. The results clearly show that as the mixture is short term aged the mechanical durability is reduced. This indicates that as the material ages its ability to resist abrasive wear is reduced, suggesting that the ability of the bitumen to bind the aggregate and rubber in the mixture is reducing with the short term ageing of the material. The cause of the bitumen losing its cohesive/adhesive strength could be the rubber-bitumen interaction, oxidative ageing of the bitumen or poorer compaction of the material for the specimens that are short term aged. Each of these factors can be assessed by changing the parameters of the mixture design to see what is causing the loss of mechanical durability through short term ageing.

6.2.2 Results on Different Mixture Designs

Different mixture designs were developed without changing the mixture grading, to investigate what factors improve the mechanical durability of the material through short term ageing as well as to investigate what ageing mechanisms are reducing the mechanical durability. The following mixture designs were mixed, short term aged, compacted into slabs and then tested in the abrasive wear test.

Rubber content change:

- 15% Rubber, 10% Bitumen, 75% Aggregate (original)
- 10% Rubber, 10% Bitumen, 80% Aggregate
- 5% Rubber, 10% Bitumen, 85% Aggregate

Bitumen content change:

- 10% Bitumen, 15% Rubber, 75% Aggregate (original)
- 12.5% Bitumen, 14.6% Rubber, 72.9% Aggregate
- 15% Bitumen, 14.2% Rubber, 70.8% Aggregate

The values above are given by mass. The changing of the bitumen content also involved changing the total dry mass of rubber and aggregate. However, the ratio of rubber to aggregate was kept constant so that the mixture volumetrics were comparable. Figure 6.3 illustrates the results from the abrasive wear test for these specimens.

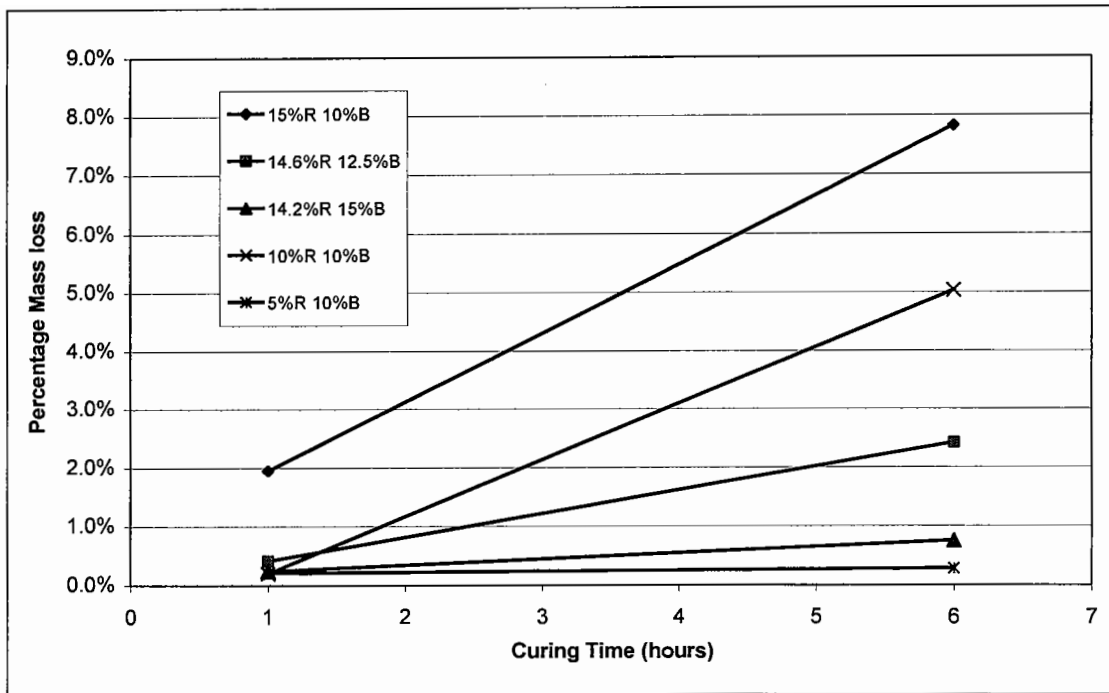


Figure 6.3 - Percentage mass loss of short term aged specimens of different 3/20 IAA mixtures

The results presented in Figure 6.3 show that by reducing the rubber content or increasing the bitumen content in the mixture, the mechanical durability of the material improves. The best result is for the 5% rubber, 10% bitumen where short term ageing of the mixture has very little effect on its mechanical durability. However, reducing the rubber content may reduce the impact absorbing characteristics of the material and will be investigated in the next chapter.

6.2.3 Results on In-situ Produced Specimens

It is important that these results are transferable for the material when laid in-situ. Testing specimens that are compacted by an in-situ method will account for conventional compaction methods, where the temperature of the mixture is not as controlled as it is in a laboratory and the compactive effort is not as great. The in-situ samples were made by following the same procedure for short term ageing in the laboratory, but instead of compacting in the pressure controlled roller compactor in the laboratory, the mixture was taken outside, placed in a large mould and compacted using a dead weight roller. This method simulated conventional compaction methods

and also accounted for the different conditions experienced when the material is compacted outside.

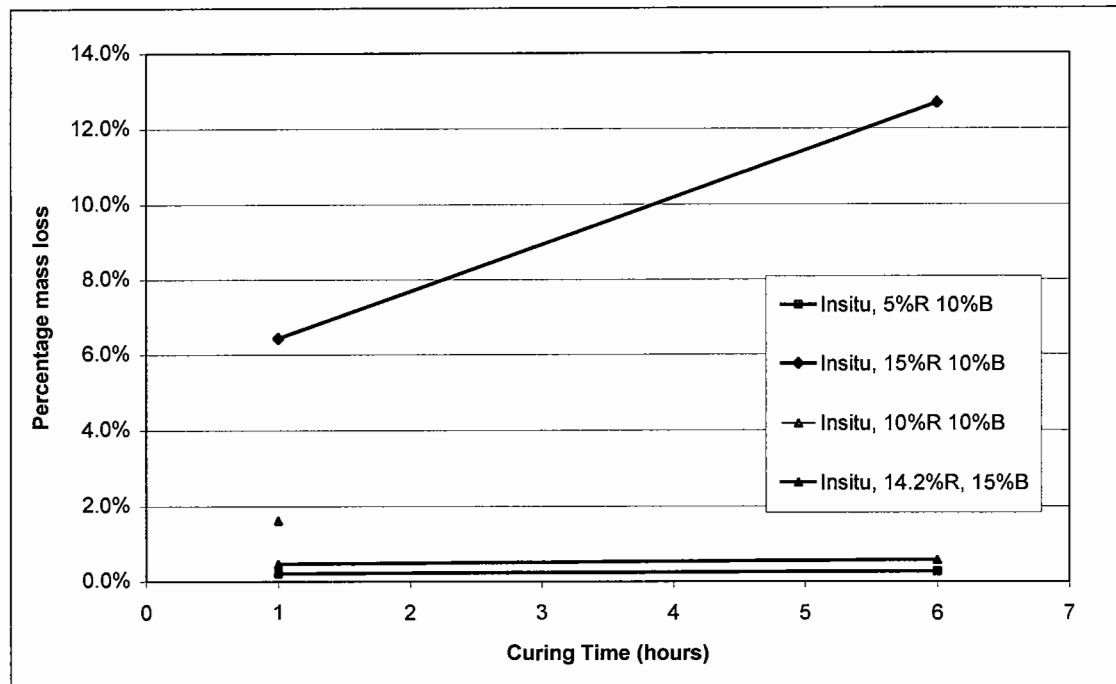


Figure 6.4 - Percentage mass loss of short term aged specimens of different mixture designs of IAA 3/20 made in-situ

Figure 6.4 presents the abrasive wear test results on the specimens made by in-situ compaction methods. It shows the same trend as the specimens compacted in the laboratory where the reduction of rubber content or the increase in bitumen content improves the mechanical durability of the material. It also shows that the magnitude of mass loss is greater for the in-situ produced specimens than the laboratory specimens. This is related to the different compaction methods, which resulted in different densities. Only one sample was made with 10% rubber to show a decrease in mechanical durability at 1 hour aged for an increase in the rubber content from 5 to 10% rubber.

6.3 Discussion

Essentially, by increasing the bitumen content or reducing the rubber content, the effect of the rubber-bitumen interaction on the mechanical durability is reduced. An increase of bitumen content in the material increases the amount of bitumen able to interact with the rubber. As shown in the Chapter 3, the amount of bitumen available

does not significantly affect the rate of interaction between the rubber and the bitumen. Therefore, the extra bitumen in the mixture will not react with the rubber and will thus be able to bind the aggregate and rubber more effectively. By the same token, reducing the rubber content will reduce the amount of bitumen that reacts with the rubber and thus more is available to bind the material.

The mechanical durability results for in-situ compacted specimens can be compared to those for the specimens made in the laboratory by considering the measured density of each specimen. Density is measured in the laboratory by weighing the sample in air and calculating its volume by sealing it and weighing it in water. For conventional asphalt, adhesive foil is typically used to seal the sample, ensuring no air is trapped on the surface. However, for IAA, because of the type of bitumen used, the foil does not bond to the sample and provide a water-tight seal so the IAA specimen is sealed by dipping in hot fluid wax. The wax coats the surface of the specimen, seals and hardens when cool. When assessing the compaction of a conventional bituminous material, the measured density is usually compared to the maximum density of the material (assuming no air voids) to calculate the air void content. There are two common methods for calculating the maximum density, one is to sum the separate masses and densities of the components in the mixture and calculate the density based on no air voids, this is known as the maximum theoretical density. This method cannot be used for IAA because of the interaction between the rubber and the bitumen. The rubber is absorbing the bitumen and swelling, thus its density changes and is difficult to calculate because the state of the interaction is hard to determine. The other method is to use the Rice method (Scholz, 1996). This involves measuring the maximum density of the material after it has been made by applying a vacuum over the sample to remove the air in the air voids. However, this method does not give accurate measurements for IAA because the vacuum applied over the material compresses the rubber, thus increasing its specific density. Therefore, it is more accurate to use just the measured density of the specimen as an indication of the compaction.

It should be noted that the density of different mixtures is no indication of the void content as they are not comparable. The specific weight of aggregate is 2.7, whereas crumb rubber is 1.05 and bitumen 1.02 at room temperature. Therefore, changing the

proportions of rubber, bitumen and aggregate also changes the maximum density of the mixture and thus the density of each mixture cannot be compared.

Table 6.1 - Difference of density and mechanical durability between laboratory and in-situ compacted specimens of IAA 3/20

Specimen	Short term ageing time	Density (kg/m ³)x10 ³			Percentage mass loss		
		Lab	In-situ	Lab-Insitu change	Lab	In-situ	Lab-Insitu change
15% R 10% B	1	1.61	1.55	+0.06	2%	6.4%	-4.4%
15% R 10% B	6	1.65	1.50	+0.15	7.8%	12.7%	-4.9%
5% R 10% B	1	1.87	1.87	0	0.2%	0.2%	0%
5% R 10% B	6	1.87	1.85	+0.02	0.3%	0.3%	0%
14.2% R 15% B	1	1.61	1.55	+0.06	0.2%	0.5%	-0.3%
14.2% R 15% B	6	1.66	1.53	+0.13	0.8%	0.6%	+0.2%
10% R 10% B	1	1.76	1.63	+0.13	0.2%	1.6%	-1.4%

Table 6.1 shows the measured densities of the specimens used in the abrasive wear test. The accuracy of the densities is $\pm 0.01 \times 10^3 \text{ kg/m}^3$ based on a 95% confidence limit for a Gaussian (normal) distribution. It shows that in general, the in-situ slabs have a lower density for the same mixture design and short term ageing time than the specimens compacted in the laboratory. This is because when the laboratory compacted specimens are made they are loaded until they have cooled. The inclusion of rubber in the mixture makes the material rebound after compaction. The in-situ compacted specimens are only compacted by a dead weight roller that is run over the slab 4 times. After compaction, the dead weight roller is removed and the slab is allowed to cool. At this stage the bitumen in the mixture is still hot and viscous. Therefore it will allow the rubber to rebound, decreasing the density of the material. This problem was recognised in the laboratory, and to improve the repeatability of the slabs made, a dead load was applied on the slabs until the material had cooled and the bitumen could restrain the material from rebounding, improving the consistency of the slabs. The one exception to the difference in densities is the mixture with only 5% rubber. It shows no noticeable change in density with the two methods of compaction,

probably due to a lower rubber content reducing the amount of rebound in the mixture after compaction.

The other noticeable difference is that for the original mixture and the mixture with 15% bitumen compacted in the laboratory, short term ageing increases the density of the mixture, whereas for the in-situ compacted specimens, the density is decreased. This phenomenon is indicative of the change in properties of the bitumen and the rubber through the interaction and the different compaction methods.

The reason the laboratory specimens have a higher density compared to the in-situ samples is because of the use of a dead load to retain the compaction of the specimen until it has cooled. The short term aged specimen can be compacted to a higher density because the rubber in the mixture has a lower stiffness and is more workable. The dead load will hold the material from rebounding because when the bitumen cools it is stiff enough to hold the rubber and aggregate together. However, some rebound will still occur although to a lesser degree than when the bitumen is hot and fluid. It is likely that because the bitumen properties are changing through the interaction with the rubber through short term ageing, the bitumen is less flexible and not able to allow much rebound. Therefore, the density of the specimens made in the laboratory increase with short term ageing because the bitumen is stiffer and the rubber is softer.

The in-situ compacted specimens do not have a dead load to retain compaction and halt the material from rebounding. The short term ageing reduces the workability of the mixture because the bitumen is stiffer and less fluid. Therefore, as the short term ageing is increased, the density of the material after compaction in-situ will be reduced. No apparent change in density between the 5% rubber mixture compacted in the laboratory or in-situ suggests that very little rebound after compaction is taking place and the interaction between the rubber and the bitumen is not significantly reducing the stiffness of the bitumen at high temperatures.

Generally, the mechanical durability of specimens compacted in-situ is poorer than specimens compacted in the laboratory. This is connected to density and degree of compaction of the specimens. The in-situ specimens are less dense and therefore have

a lower degree of compaction than the laboratory specimens. If the material is not well compacted then the bond between particles within the mixture is less extensive, due to the presence of more air voids. Therefore, the particles can be removed easier as the in-situ compacted specimens having a lower density.

However, the reduction in density is not the sole cause of a reduction in mechanical durability of the material. It was noted at the beginning of this chapter that the cause of the reduction of mechanical durability through short term ageing could be due to rubber-bitumen interaction, oxidative hardening of the bitumen or reduction of compaction due to the ageing. If the reduction in density due to ageing is the main reason for the poor mechanical durability, the specimens short term aged for 6 hours and made in the laboratory would show an increase in mechanical durability because their density has increased. However, the mechanical durability has decreased suggesting that another factor is the more significant.

It can also be concluded that oxidative hardening is not the major cause of the reduction in mechanical durability. Oxidative hardening of the bitumen takes place during the life of the bitumen and is particularly active during the short term ageing of conventional bituminous materials. It involves an increase in the stiffness of the bitumen, which makes it more brittle and susceptible to fracture. Therefore, short term ageing of the material is likely to cause the bitumen to harden through oxidation and fracture easier under loading in the Abrasive Wear Test. This will allow the particles to work free and thus reduce mechanical durability. However, although this is likely to contribute to the decrease in mechanical durability through short term ageing it is not the major factor as the rubber content also reduces the mechanical durability. If oxidative hardening was the major contributor to the reduction in mechanical durability, changing the rubber content would not significantly alter the performance of the material. However, Figure 6.3 and Figure 6.4 both illustrate that reducing the rubber content does increase the mechanical durability significantly. Therefore, the main contributor to the reduction of mechanical durability of the material is the rubber-bitumen interaction.

6.4 Summary

The Abrasive Wear Test has been used to quantify the changes in mechanical durability of IAA through short term ageing, reducing the rubber content, increasing the bitumen content and changing the compaction method. It has shown that the interaction between the rubber and the bitumen is the main contributor to a reduction in mechanical durability through short term ageing.

The production of IAA was analysed and a short term ageing protocol was developed that simulated the construction process of the material. This period of the life of the material was thought to be where the interaction between the bitumen and rubber is most active because the material is held at an elevated temperature. Initial testing on the original mixture demonstrated that short term ageing significantly reduced the mechanical durability of the material. This was found to be due to the interaction between the rubber and the bitumen reducing the amount of bitumen able to bind and also reducing the cohesive/adhesive strength of the remaining bitumen thereby reducing its ability to bind the aggregate and rubber together.

The mixture design of the original material was altered to investigate methods of reducing the affect of the rubber-bitumen interaction on the mechanical durability. The rubber content in the mixture was reduced and this was found to increase the mechanical durability of the material and showed no significant change through short term ageing. An increase in bitumen content also improved the mechanical durability of the material, although short term ageing did reduce it by a small amount.

The change in mechanical durability through using conventional compaction methods was investigated. It showed that laboratory specimens were compacted to a higher density because a dead load is applied to the compacted specimen until it cools, so it is not able to rebound as much after compaction. It also indicated that the material, when short term aged, became more workable as a result of the rubber reducing in stiffness due to the interaction with the bitumen and also the aged bitumen being less flexible at ambient temperatures and halting the rebound. The density of in-situ compacted specimens was decreased for the aged specimens due to the increase in stiffness of bitumen when compacting. Measuring the different densities of the

specimens also showed that although the degree of compaction has an effect on the mechanical durability, it is not the major contributor to the changes.

Oxidative hardening of the bitumen through short term ageing was also investigated as a contributor to the reduction in mechanical durability. However, because the effect of reducing the rubber content has a pronounced affect on the mechanical durability, the rubber-bitumen interaction is clearly the major mechanism that is reducing the mechanical durability of IAA through short term ageing.

The main advantage of using IAA as a playground surface is that it can provide a cost effective shock absorbing layer to reduce injuries from accidental falls. The effect of reducing the rubber content or increasing the bitumen content have clearly demonstrated an increase in the mechanical durability of the material. However, it has to be established how these changes affect the impact absorbing properties of the material and its ability to reduce injuries so that it can perform as a safety surface.

7. IMPACT TESTING OF SPORTS AND SAFETY SURFACES

7.1 Introduction

The dynamic stiffness of a material can be described as its ability to resist deformation from impact loading. This is of particular importance when considering a sports or safety surface. It is generally agreed that a safety surface with a lower stiffness (e.g. for playgrounds) will reduce injury by providing a cushioning effect on impact (Nigg, 1989). Whilst it is equally important for sports surfaces to reduce the impact forces on a subject, it should also be noted that a decrease in stiffness can produce a loss in the performance of the surface (Frederick, 1984). If the surface stiffness is too low, the subject cannot move, jump or run effectively. Therefore, a balance must be struck between the safety and the performance of a sports surface.

This chapter describes the development of an impact test for assessing the impact absorbing properties of Impact Absorbing Asphalt (IAA). A number of different impact performance tests are assessed that led to the adoption of the Impact Attenuation Test as a suitable test for IAA. The development of the test equipment and procedure will be detailed to prove that the test produces reliable and repeatable results as an evaluation tool for the impact absorbing properties of IAA.

7.2 Impact Performance Testing

Most bituminous materials are visco-elastic which means that the material possesses both elastic and viscous properties. The balance of the properties depends on temperature, rate of loading and the material. Therefore, the measured stiffness from an impact test can vary greatly depending on the test conditions. Generally, impact testing of a material involves applying a load over a very short time and thus testing the stiffness or mechanical properties of the material at a high rate of loading.

7.2.1 Performance Tests

The dynamic response through impact of the surface is an important parameter to measure because it can be used to characterise the performance of a surface and assess

its ability to reduce impact stresses. A number of tests in different countries have been developed over the past 30 years, which all measure (directly or indirectly) the stiffness or impact absorption properties of the material. Listed below are a number of these tests that are briefly described in the following sub-sections.

- 1) Ball Rebound (Dury, 1979)
- 2) 'Sportest' Resilience Tester (Brevet, 1970)
- 3) 'Stuttgart' Artificial Athlete (Dury, 1979 and Frederick, 1984)
- 4) 'Berlin' Artificial Athlete (Frederick, 1984)
- 5) Assessment of Impact Attenuation (Dury, 1979 and Nigg, 1989)

Ball Rebound

Ball rebound is perhaps one of the only tests that relates to practical conditions. In this particular case Dury (1979) carried out research in Nottingham into the ball rebound requirements for cricket pitches. A cricket ball was dropped vertically from a height of 4.8m and the rebound height was recorded and related to the performance of the pitch. This is really an in-situ test and the results are dependent on the substrate, climatic conditions and surface texture. These parameters cannot easily be replicated in the laboratory. For this series of tests only the rebound height was used as a measure of the performance of the cricket wicket because the initial conditions were constant. However, the resilience (R) can be related to the rebound height using:

$$R = E_R/E_T \quad 7.1$$

where;

E_R = reflected energy \propto (rebound height)²

E_T = incident energy \propto (effective drop height)²

The term R as a measure of resilience also relates to the coefficient of restitution of an impact which is the ratio of rebound velocity to impact velocity.

Artificial Athlete

The response of the surface due to impact loading is dependent on the time of loading. The artificial athlete was developed to simulate the impact from a normal person running on the surface.

Figure 7.1 shows the shape of a typical vertical ground reaction force-time history for a person running. The trace on the graph can be divided into two main areas; the initial peak represents the heel striking the ground and the second longer impulse results from the rest of the foot carrying over and then pushing off to take the next step. To measure the impact performance of sports surfaces, two tests were developed; one to simulate the short impact of the heel and another as the second longer impact from the carrying over and then pushing off. The two artificial athletes are based on similar apparatus, the 'Stuttgart' Artificial Athlete and the 'Berlin' Artificial Athlete (Frederick, 1984).

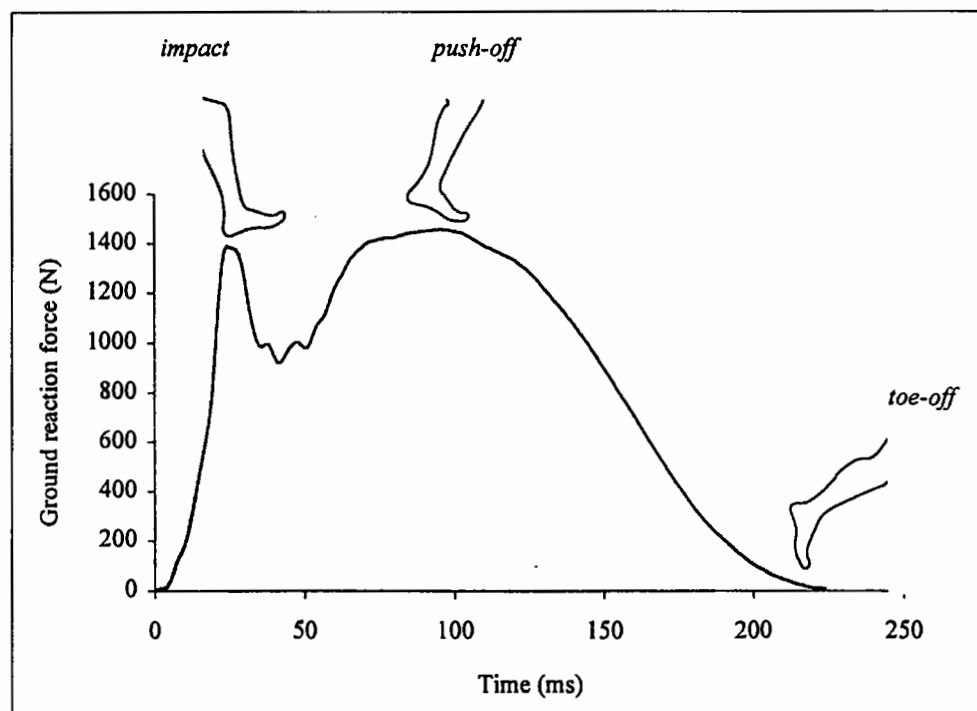


Figure 7.1 - A typical vertical ground reaction force history for heel-toe running (Dixon, 1997)

The 'Stuttgart' artificial athlete was developed at the Otto-Graf Institute in Stuttgart. The force-time relationship that corresponds to a pulsed loading rise time with a duration of 140-150ms is measured and relates to the second phase of the impact. The

apparatus consist of a weight that falls onto a spring which distributes the load over the desired impact time and transfers it to the spherical test foot.

The variables that can be measured with this apparatus are the reaction force, the deformation of the surface and the loss of mechanical energy of the surface. Conventionally, the maximum force of the impact and the deformation of the surface under the test foot are monitored.

In comparison, the 'Berlin' Artificial Athlete was designed to apply a shorter loading time to simulate the impact of the heel of a runner. A loading curve of about 10ms duration is applied to the surface by increasing the stiffness of the spring. The maximum force is measured by a force transducer and the resilience of the surface is described by a 'force reduction' defined as the proportion of the maximum force experienced on a rigid floor. The force reduction for concrete is 0%, whereas gym mats can be in the region of 90%. The advantage of this method is that it only measures the force, so time is saved by not using deflection transducers.

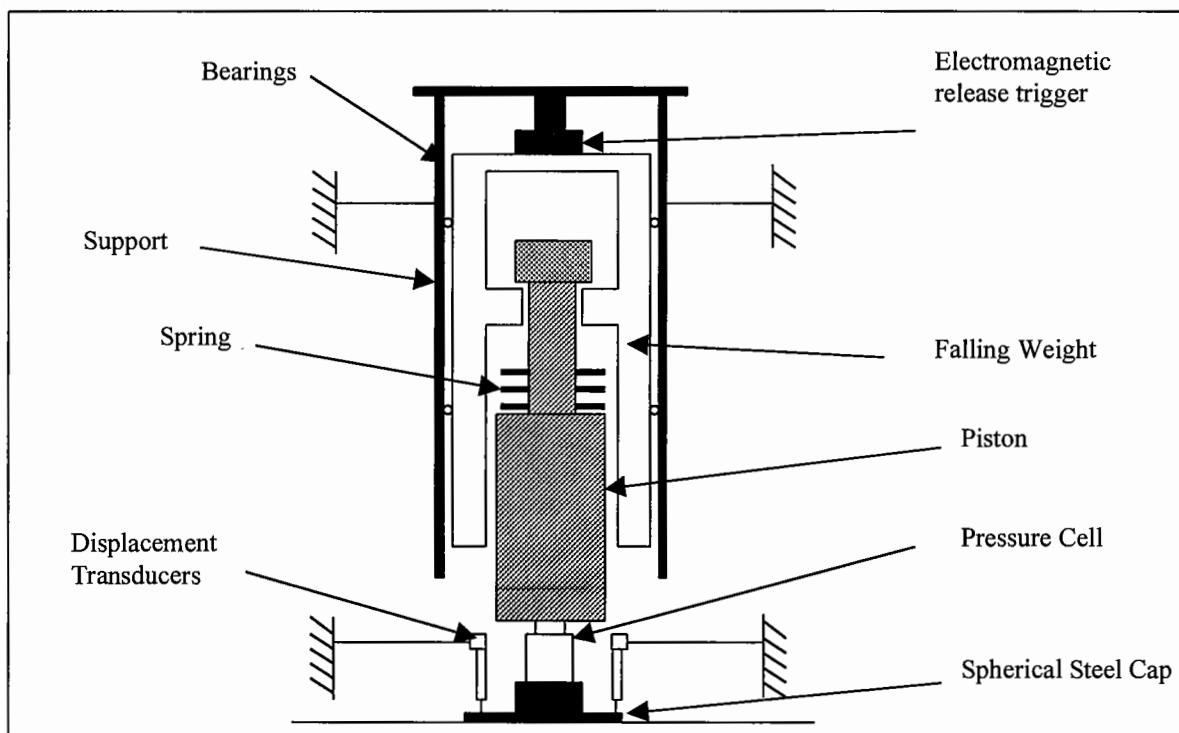


Figure 7.2 - Arrangement of the 'Stuttgart' and 'Berlin' Artificial Athlete (Nigg et al., 1989)

Table 7.1 shows the test equipment data, illustrating the difference in parameters used to model the two stages of impact from a person running on the surface.

Table 7.1 - Characteristic data for the two Artificial Athletics, Stuttgart and Berlin shown schematically in Figure 7.2 (Kolitzus, 1984)

Apparatus	Unit	Stuttgart	Berlin
Falling Weight mass	kg	50.0	20.0
Test foot mass	kg	9.0	1.8
Spring Constant	kN/m	50	2000
Drop height	m	30	55
Test foot diameter	mm	49.5	70.0
Impact velocity	m/s	$\cong 0.7$	$\cong 1.0$
Rise time at impact	ms	$\cong 150$	$\cong 10$

Sportest Resilience Tester

The 'Sportest' was developed for assessing running tracks in France (Brevet, 1970). The equipment is designed to measure the deflection of the surface under an impact load that imposes a 1.2kN force for a duration of 120ms by means of self damped springs. The idea of this test is to simulate the impact between the heel and ground when running. Sensors record the deflection under the centre of the load and the maximum rebound velocity in mm/s.

7.2.2 Discussion

The last three methods described have all involved the use of a spring to alter the impact time and simulate the motion of a human. Nigg (1989) illustrated that from work by Denoth (1978) there are two inertia terms ignored when assessing surfaces in this way. During the impact phase various masses are decelerating or accelerating; the drop mass, the test foot and part of the mass of the surface. These accelerating or decelerating masses can be shown to influence the test results by measuring the forces underneath the surface as well as those above. The equation of motion given in Equation 7.2 illustrates the forces involved;

$$F_A(t) = F_{FP}(t) - m_s \cdot a_s(t) - m_f \cdot a_f(t) \quad 7.2$$

where;

- $F_A(t)$ = force measured on the dropping mass
- $F_{FP}(t)$ = force measured underneath the surface, i.e. force platform
- $m_s \cdot a_s(t)$ = inertia term due to the movement of parts of the surface sample
- $m_f \cdot a_f(t)$ = inertia term due to the movement of the test foot

The magnitude of the surface-related inertia term is dependant on the type of surface. For point-elastic surfaces which only deflect at the point of impact, such as cinder tracks and some gym mats, the mass that is moved is small and this term can be ignored. However, for area elastic surfaces such as gym floors, which are essentially pin supported beams, the area affected is large and the inertia due to the movement of the surface is significant.

The inertia term due to the movement of the test foot depends on the mass of the test foot and its acceleration. Maximum values for acceleration of the test foot are about 300m/s^2 (approx. 30g). The mass of the test foot for the Stuttgart AA is 9kg and is 1.8kg for the Berlin AA. This corresponds to possible inertia terms up to 2.7kN for the Stuttgart AA and 0.5kN for the Berlin AA. These values can be significant but do not appear to have been taken account for in literature describing these test procedures by Kowitz (1984).

7.2.3 Impact Attenuation Test

Under impact, the body can be exposed to acceleration, force, pressure, stress and strain. To assess the performance of a surface, it is more practical to select one of these parameters for measurement that relates to a particular injury. For head injuries it is very difficult to obtain measurements that are directly associated with injury, such as pressure, force or stress. As a result, the overall head deceleration, an indirect measure of the force, has been used. The impact attenuation test has been developed to model the impact of a child's head striking a surface. This is the most common cause of injury and extensive research by Lombard et al.(1951) and Colonel Stapp (1957) has been carried out to relate the head impact to internal injury to the head.

The impact attenuation test is designed to measure the deceleration during impact between a hemispherical head form of known weight, dropped from a known height onto a surface. This test configuration has no other moving parts apart from the head form, therefore reducing the inertia in the system. It is designed to simulate the impact of accidental falls and was developed through studies of automobile and aeronautical accidents. The magnitude and shape of the resulting deceleration verses time graph have been related to injury tolerance data and can be used to estimate the degree of likely injury hazard, particularly to the head (Bowers et al., 1974).

A schematic view of a typical deceleration pulse obtained from the impact test is shown in Figure 7.3. A number of parameters can be obtained from this time history. The maximum deceleration, or “peak g”, is the most widely used rule-of-thumb measure of injury hazard because it is the simplest. However, it has been recognised that the peak deceleration cannot accurately define the response of the head to impact. In particular, work carried out by Patrick (1965) showed that the degree of tolerance to deceleration was also a function of the duration of the deceleration. This work, carried out on cadavers and animals, showed that very high accelerations can be tolerated briefly. Therefore, injury to the skull is a function of the intensity and the duration of loading and not solely to the peak deceleration. Work by Gadd (1966) led to the use of the weighted area under the deceleration-time curve, as a measure of injury. Mathematically this can be expressed as;

$$SI = \int_{t_1}^{t_2} a(t)^n dt \quad 7.3$$

where;

- a = acceleration of the response function
- n = weighting factor (greater than 1)
- $t_2 - t_1$ = duration of pulse (seconds)

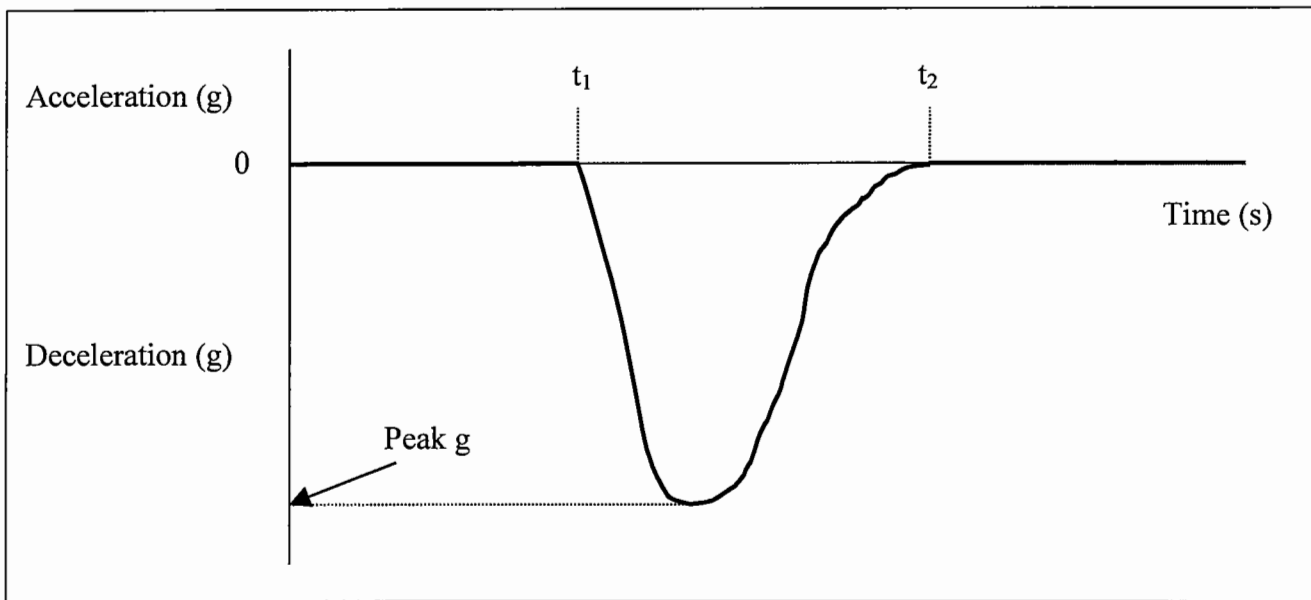


Figure 7.3 – A typical impact plot from the impact attenuation test

Equation 7.3 is commonly known as the severity index (SI) and incorporates the fact that impact-induced injuries may be predominantly affected by higher values of acceleration, whilst the lower values contribute relatively little. This equation was found to give good correlation with biomechanical data using a weighting factor of $n = 2.5$. Gadd (1966) also suggests, based on the work by Patrick (1965), that using this formula a numerical value of $SI \geq 1000$ would represent a danger to life. It should be noted that this is only justified for internal head injuries from frontal head impact only.

Subsequent to this research, the British Standards Institution (BSI) adopted the SI as a measure of performance for children's playgrounds which is incorporated in BS EN 1177 (1998), the standard for impact absorbing playground surfaces. The British Standard for artificial sports surfaces (BS 7044:Section 2.2 [1990]) still utilises the 'peak g' method because the large number of different injuries that can be sustained have not been quantified in as much detail as head injuries. The peak deceleration is used as a measure of the ability of the surface to absorb the energy of a player falling on to it. However, both standards use the same apparatus illustrating that the impact test can be used as a measure for both types of surface.

It should be noted that, although this test has been adopted as a standard performance measure for both sports and playground surfaces in the UK it still has some problems. The magnitude of the maximum deceleration and the time of loading is dependant on the mass, radius and impact velocity of the striker. Work carried out by Nigg (1989) suggests that a change in one of these factors effects not only the measured impact forces but also the ranking of surfaces based on impact results.

Figure 7.4 illustrates that if the surfaces were to be ranked using the larger mass ($m=7.3\text{kg}$) then the surface with the lowest impact forces would be A, whereas for the smaller mass ($m=4.0\text{kg}$), surface C would provide the lowest impact force. This shows that the user cannot be sure that the results are due to changes in the test set up or in the material. Therefore, to enable a confident ranking system, the standard procedures in BS 7188 and BS 7044 must be adhered to.

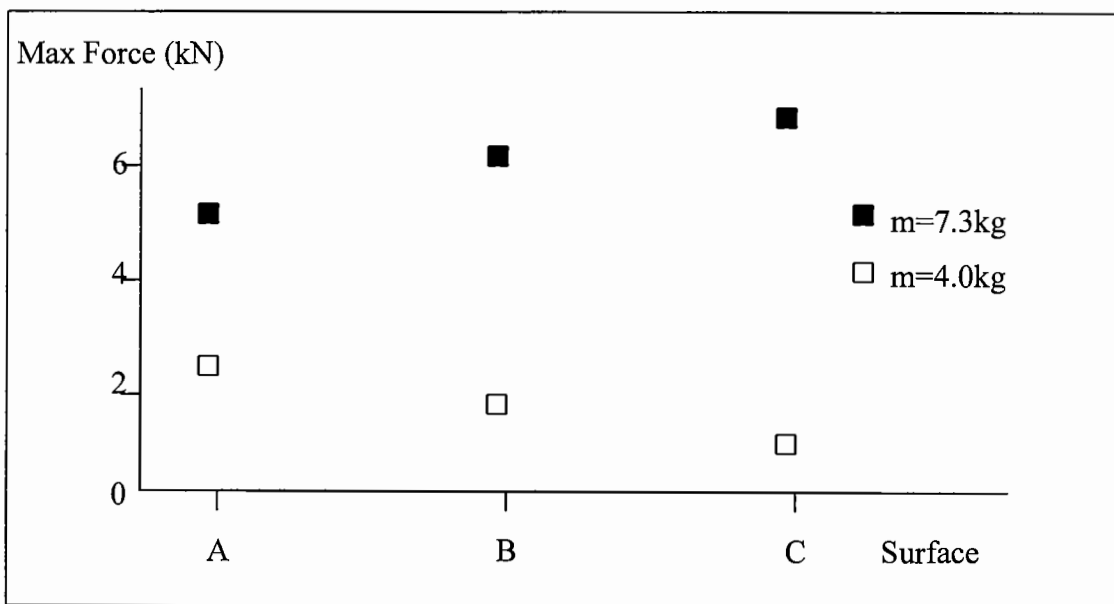


Figure 7.4 - Maximum force determination with two different shots, one shot with mass 7.3kg and a radius of 6.2cm and a second shot with a mass of 4.0kg and a radius of 5.2cm. The touch down velocity was 2m/s and the thicknesses of the three surfaces ranged between 20 and 21mm (Nigg, 1989).

7.2.4 Summary of Impact Performance Testing

A number of tests used to measure the stiffness and impact absorbing properties of the materials have been described. It has been illustrated that tests used to simulate the

loading time associated with a human running on the surface are not clear simulations for measuring the impact resilience of the material because the inertia of the test apparatus is not measured. It has also been shown that the impact attenuation test used by the British Standards for sports and safety surfaces is sensitive to the radius and mass of the impact head form.

The impact attenuation test has been adopted for research for this project because it is the simplest existing measurement of impact absorbing properties. It is also the British Standard performance test for assessing sports and playground surfaces and therefore can be used to compare other test results on different sports and safety surfaces. The effect of changing the head form size need not be addressed as long as the head form is kept identical to the test described in the British Standard.

7.3 Impact Test Development

The impact attenuation test at the University of Nottingham has been built and developed based on the test apparatus described in BS EN 1177 (1998). This section describes the experimental procedure for the test and then describes the development of the test apparatus. It will also outline the test procedure developments so that the experiment follows the standard procedure and gives accurate measurements of the impact resilience of IAA.

7.3.1 Experimental Procedure

The basic equipment for the impact attenuation test set out in BS EN 1177 (1998) and BS 7044 (1990) consists of a hemispherical head-form of diameter 16.5cm with an accelerometer fixed to it and a rigid solid surface onto which a sample is laid (see Figure 7.5). The head-form is raised to a pre-determined height and dropped onto the sample. The total mass of the head form that impacts the sample must be 6.8+/- 0.01kg. An accelerometer is mounted inside the head form and is connected to a signal conditioning unit and a personal computer.

The principle of the impact test is to drop the mass (under free fall conditions) onto the surface from different heights and record the deceleration of the head form as it

impacts the surface. There are a number of experimental designs that could achieve this. The test equipment defined in BS 7188 (1989) utilises a 6.8kg hemisphere falling without guidance (free fall) and a triaxial accelerometer arrangement so that non-vertical accelerations can be accounted for. The apparatus at The University of Nottingham, was designed so that the head form moves in only the vertical plane using guidance columns, approximately 1m apart. A single uni-axial accelerometer is used to measure the vertical deceleration on impact with a surface. A schematic of the first prototype impact rig at The University of Nottingham is shown in Figure 7.5.

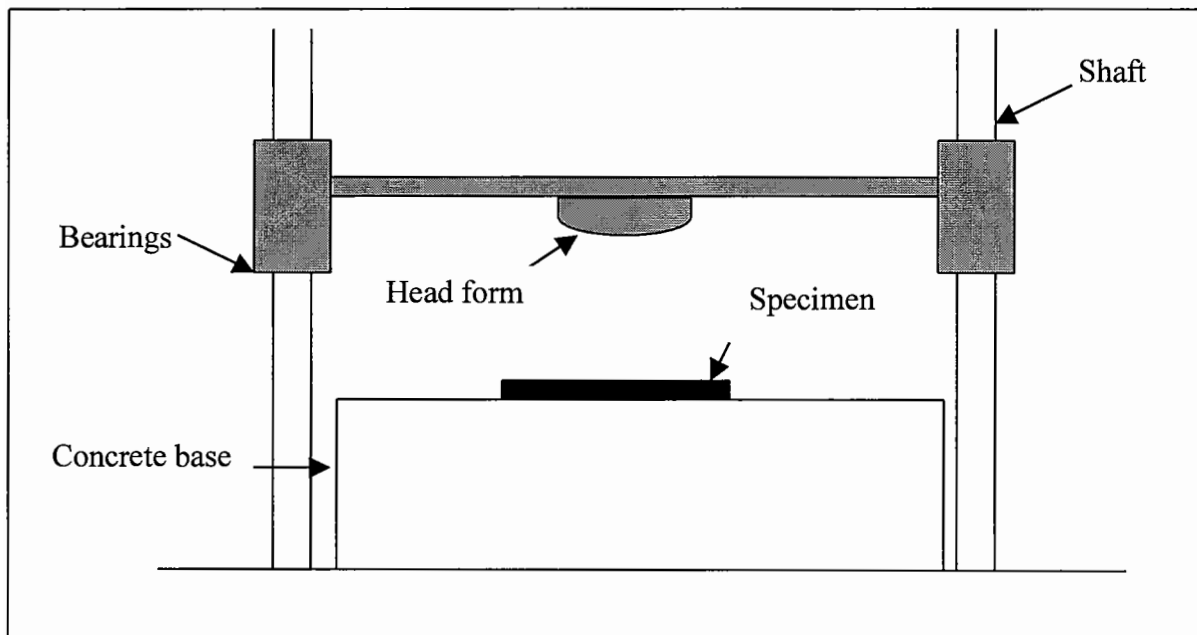


Figure 7.5 – Diagram of Impact Attenuation Rig Mk I at Nottingham University

The acceleration data can be used to calculate the peak deceleration (peak g) or the severity index. As discussed in Section 7.2.3, the peak g is used as an indication of the impact absorbing properties of sports surfaces and the severity index is related to the weighted area of the acceleration-time plot and is the measurement parameter for impact absorbing materials on children's playgrounds.

7.3.2 Equipment Development

First Prototype

The first prototype designed and developed at the University of Nottingham is shown schematically in Figure 7.5. It shows a hemispherical head form (made out of aluminium) attached to a hollow rectangular section bar of cross-section (50 x 25 x

1.6mm thickness). The bar spans between two guide poles (1m apart) that are each straddled by a bearing which are attached to the bar. The total mass of the head form, the bearings and the bar is 6.8 ± 0.01 kg. A typical acceleration versus time plot measured from this set up is shown in Figure 7.6 for a drop height of 0.7m (the data has been processed using a 10kHz low pass filter.)

This figure shows that after the impact, the head form is apparently subjected to large relatively lightly damped accelerations. The first pulse, between points A and B, is the impact trace where the head form is in contact with the surface. After point B the head form is assumed not to be in contact with the surface and the only force acting should be due to gravity (1g). Therefore, the accelerometer should measure unity as the head form bounces off the surface but Figure 7.6 shows that after point B the accelerometer is recording values fluctuating in excess of ± 70 g. Therefore, the acceleration measured in the head form is not only due to the impact on the surface of the material. The indication is that the accelerometer is recording vibrations of the equipment due to the impact.

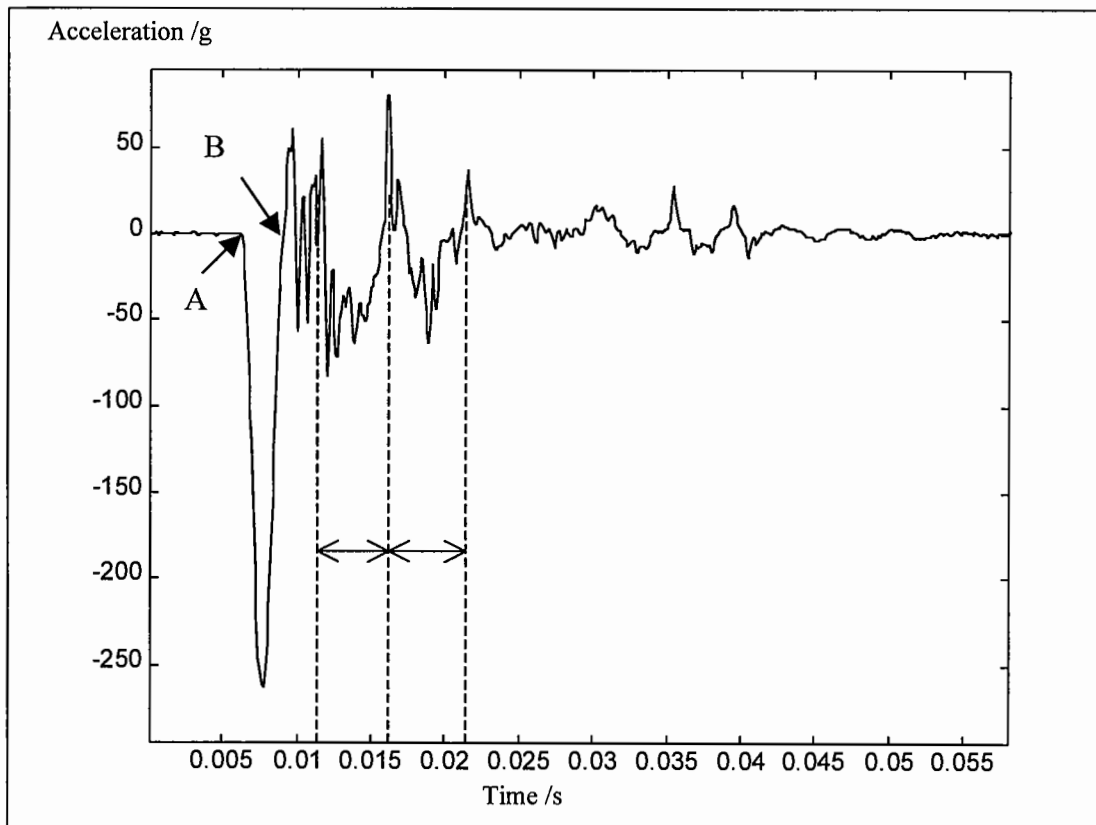


Figure 7.6 - A typical impact trace using the Impact Attenuation Rig Mk I

These vibrations are occurring because the majority of the mass of the moving parts is located in the bearings outboard of the central head form. This would not be a problem for a perfectly rigid bar because the energy loss to vibrations would be zero. However, because of the weight restriction, the bar is lightweight and therefore has a certain amount of flexibility allowing a greater proportion of the energy of the impact to be transferred to vibrations in the bar. The time between peaks of acceleration marked on the figure as t , suggest that the system has a dominant frequency of $1/t$ which equates to approximately 165Hz. A simple mechanical model that was used to represent the system when the head form is in contact with the material is shown in Figure 7.7.

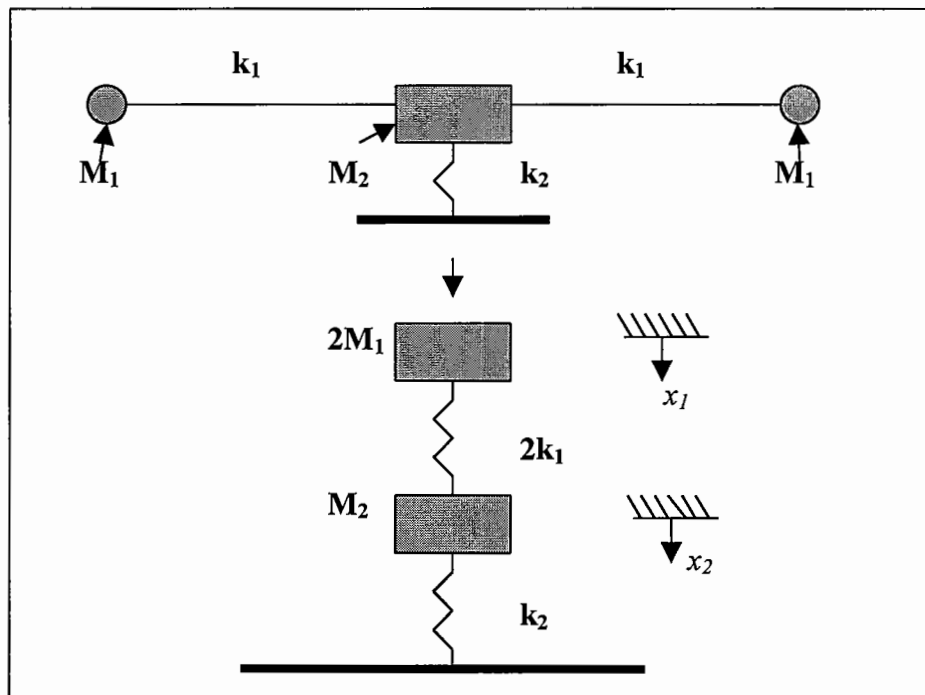


Figure 7.7 - Simple model to illustrate the impact characteristics due to unlocalised loading

The mass M_1 is associated with the mass of the bearings and part of the bar, k_1 represents the bending stiffness of the bar. The mass M_2 represents the mass of the head form and the remainder of the bar and k_2 is the contact stiffness of the material being impacted. (It should be noted that in reality the contact stiffness will not be linear). This model has been used to assess the effect of bar flexibility on the resulting deceleration-time curves. The mass of the bar and bearings was estimated to be 4kg (i.e. $2M_1=4\text{kg}$) and the mass of the central head form was estimated to be 2.8kg (i.e. $M_2=2.8\text{kg}$). Using the model shown in Figure 7.7 it can readily be shown that the matrix equation of motion is given by:

$$[M] \frac{d^2 X}{dt^2} + [K] X = [0]$$

7.4

where;

$$X = [x_1, x_2]^T$$

$$[M] = \begin{bmatrix} 2M_1 & 0 \\ 0 & M_2 \end{bmatrix}$$

$$[K] = \begin{bmatrix} 2k_1 & -2k_2 \\ -2k_1 & 2k_1 + k_2 \end{bmatrix}$$

Equation 7.4 can readily be solved provided 2 initial conditions are known (i.e. $x=0$ at $t=0$ and $dx/dt=\sqrt{2gh}$ at $t=0$). Figure 7.8 shows the numerical solution to this equation and the solution to the single degree of freedom problem assuming $M_1=0\text{kg}$ and $M_2=6.8\text{kg}$. The driving force is from a typical impact from a drop height of 0.6m.

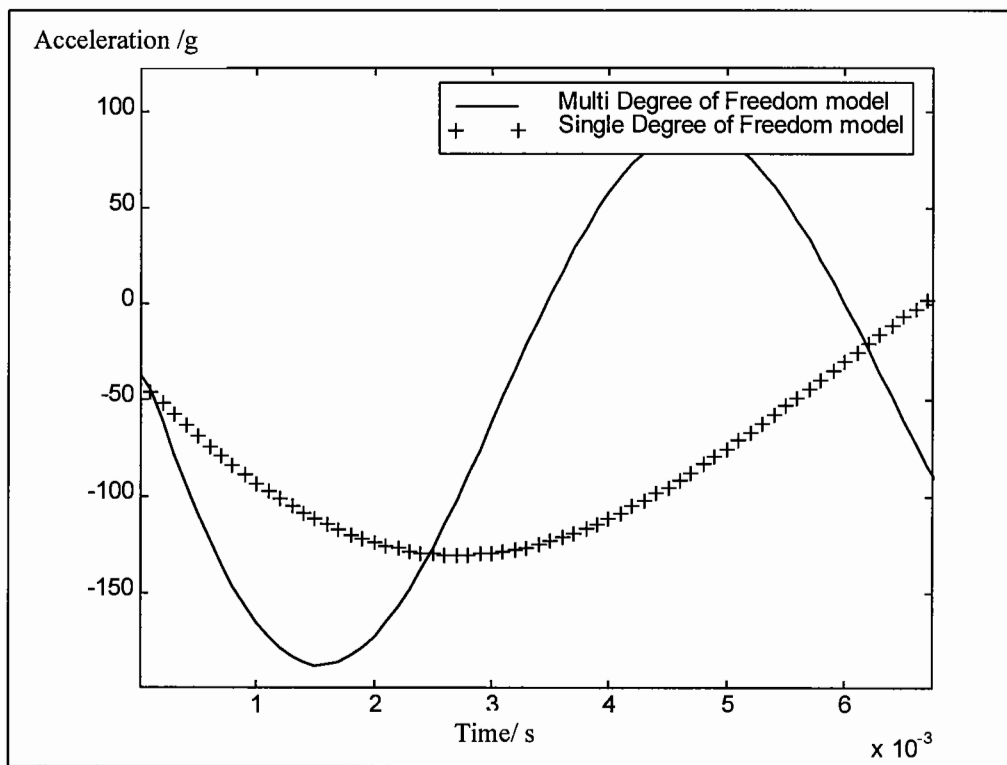


Figure 7.8 - Response acceleration-time curve for two impact rig models

Using simple bending theory the bending stiffness of the bar (k_1) was estimated to be 0.4MN/m and the contact stiffness was estimated to be 1.3MN/m¹ giving two natural frequencies of contact of 50Hz and 150Hz. Equating to a similar frequency of 165Hz shown to dominate on the impact trace of the Impact Rig Mk I. In comparison, if $M_1=0$, the system has only one degree of freedom and the natural frequency of the contact is 70Hz. It should be noted that this model is only valid whilst the mass is in contact with the surface although the beam vibration will continue after contact.

It can be seen from this figure that, due to the flexibility in the bar, the acceleration response of the system is different from the simpler single degree of freedom system. This results in a higher value of peak deceleration and a shorter time to the first point where the acceleration curve crosses zero. (Note that in the case of the 2 degree of freedom system this is not the impact time since the head form is still in contact with the surface).

The next stage was to re-design the rig so that the 6.8kg mass is concentrated above the impact point to eliminate the problem of bar vibrations.

Second Prototype

The criteria for re-designing the rig were as follows:

- 1) To eliminate vibrations in the bar
- 2) To utilise the existing dropping mechanism
- 3) To ensure a uni-axial drop to utilise the uni-axial accelerometer.

The simplest and most effective way to satisfy all these criteria was to use the existing guide poles and de-couple the impacting mass from a cross-bar so that upon impact the impacting mass is not in contact with the cross-bar. Figure 7.9 shows a schematic of the second prototype that was developed to satisfy these design criteria.

¹ The contact stiffness of the surface is estimated from a real trace shown in Figure 7.10, assuming a sinusoidal contact; $k_2=m_2*\omega^2$ where $\omega=2\pi f$ with f being equal to the contact frequency.

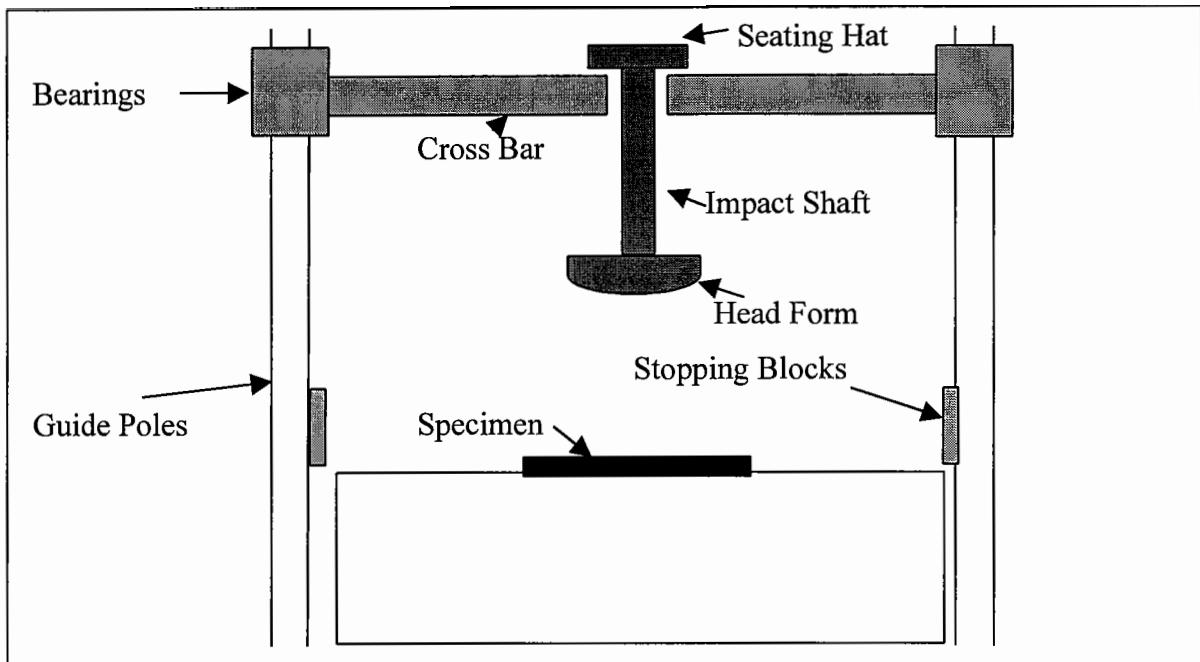


Figure 7.9 - A schematic of the Impact Attenuation Rig Mk II

A larger bar was used to straddle the two guide poles allowing higher quality bearings to be used which improved the consistency of the drops. The impact mass was concentrated in the aluminium head form, the impact shaft and the seating hat which were directly above the impact point. The seating hat located the impact mass in a cylinder held in the centre of the cross bar and held it in a vertical position perpendicular to the slab. The procedure for the test was to drop the cross bar, holding the impact mass. When the head form comes in contact with the specimen, it will start to decelerate and the accelerometer fixed in the head form records the impact trace. The impact mass was not restrained, only seated via the seating hat and when the impact occurred the cross bar released the impact mass at the seating hat and continued to move, halted after the impact by the stopping blocks on the guide poles. Therefore, only the 6.8kg mass centred over the impact area was striking the specimen.

This system eliminates the vibrations due to the flexibility of the cross-bar in the Mk I Rig by de-coupling the bar from the impact mass. A typical impact trace from the second prototype is given in Figure 7.10. The data was recorded at 10,000 samples per second and filtered using a 5kHz low pass filter.

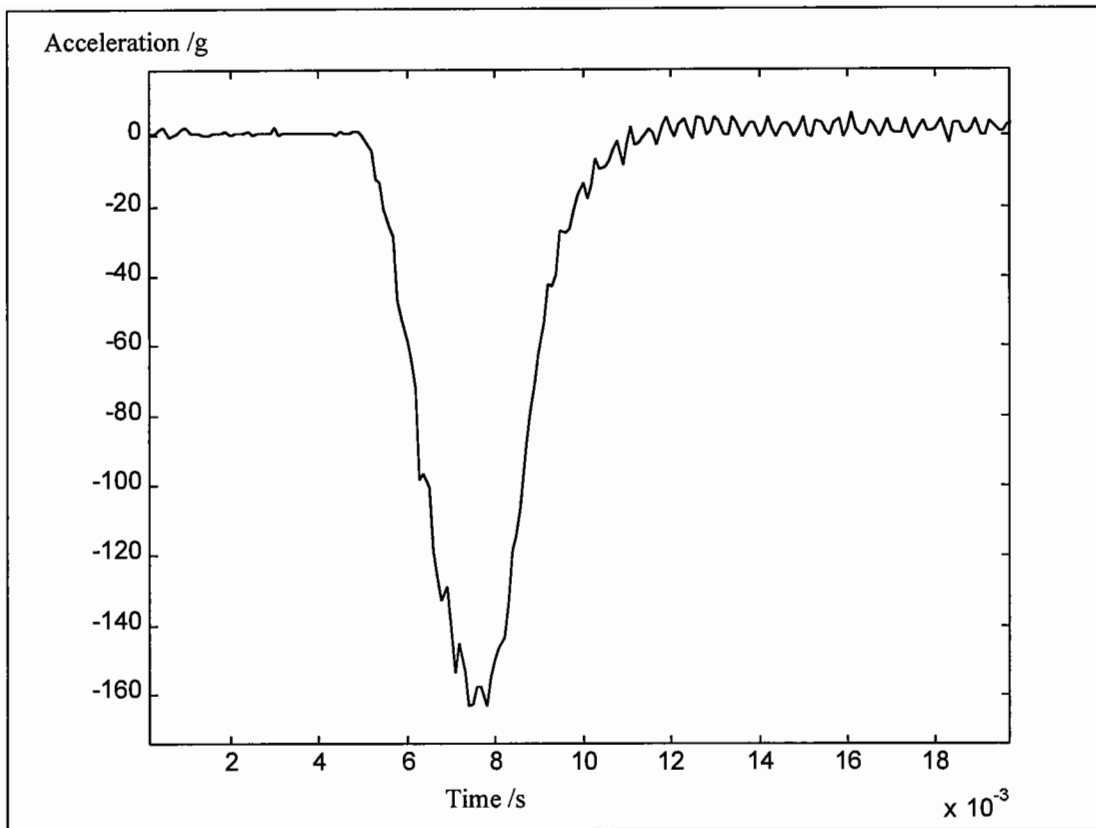


Figure 7.10 - Impact trace using Impact Rig Mk II on IAA 10/40, 0.6m drop, 5kHz filter

This result shows an impact pulse length of 7ms (i.e. the time the headform is decelerating), indicating an approximate impact frequency of 70Hz and a peak g of 165g. In comparison, the impact rig Mk I for the same material and from the same drop height gave an impact time of 4ms corresponding to an approximate frequency of 125Hz and a peak g of 200g. It can be seen from the model shown in Figure 7.7 that the predicted differences between the models are broadly similar to those found between the Mk I and Mk II prototypes. This shows that the second prototype has a better correlation to the simple single degree of freedom model that the test is designed to duplicate. The trace shown in Figure 7.10 also shows that the vibrations after the impact that were detected with the first prototype have been significantly reduced.

However, the trace on Figure 7.10 illustrates some sharp undulations at the point of impact on the trace that represent higher frequency vibrations. To investigate this

phenomenon in detail, the filter was removed and the drops were repeated. Figure 7.11 shows a typical unfiltered trace measured from the prototype, Mk II.

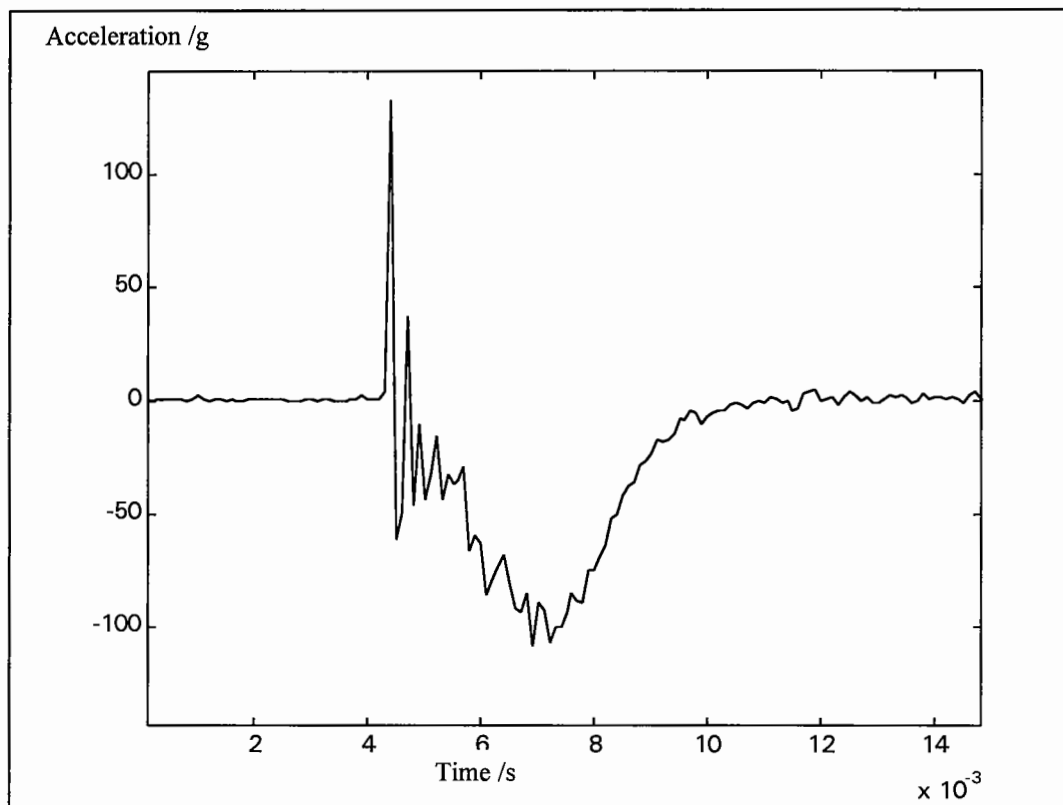


Figure 7.11 - A typical unfiltered Impact trace on IAA 10/40 using the Mk II Rig, sampling rate=10kHz, unfiltered

It can be seen from the figure that, at the point of impact, a high frequency disturbance is propagated as well as the expected lower frequency impact trace. This disturbance is thought to be due to high frequency vibrations in the head form and is caused by the non-homogenous nature of Impact Absorbing Asphalt (IAA). IAA is a matrix of rubber and aggregate bound together by bitumen. The surface of IAA is therefore a mixture of soft rubber and hard aggregate. When the head form strikes the surface, the surface deforms because the rubber around the aggregate cushions the impact. The harder aggregate, deflecting because it is held in the rubber matrix, will strike the metal head form, exciting high frequency vibrations within it. These vibrations decay rapidly but they do affect the impact trace and can alter the peak deceleration and severity index. These vibrations can, as shown, be filtered out. This will remove the inconsistency of the readings but will also influence the peak deceleration (peak g) and severity index.

Third Prototype

The Mk II impact rig utilised an aluminium head form with most of the impact mass being in the shaft. Therefore, the head form is relatively light allowing more energy to be transferred into vibrations of the head form where the accelerometer is mounted. The third prototype was designed to reduce the amount of impact energy that is transferred into vibrations of the head form at impact. To do this, the design was kept similar but the mass of the head form for the Mk III impact rig was increased by making it out of steel and the shaft was made out of hollow steel section. This concentrates the mass in the head form, making it stiffer, resulting in a lower proportion of the impact energy able to be transferred into vibrations of the head form.

Although this design reduced the amount of vibrations in the head form and shaft, they still occur, affecting the impact trace. To eliminate the vibrations completely without losing data would be very difficult. To reduce the vibrations a low-pass filter was used to smooth the trace for consistency by removing the high frequency data, but an unfiltered trace was recorded at the same time from the same data but onto a second channel in the signal processing unit. Therefore, the amount of data lost due to filtering can be monitored and accounted for if necessary.

A repeatability study was carried out to quantify the effect of filtering the acceleration data from the impact. Twenty drops were made from the same height (0.4m) and the signal was filtered at 3.6kHz using a low pass Cheychev filter. The same signal unfiltered was also recorded at the same time using a separate channel on the data logger. A typical result is shown in Figure 7.12.

The repeatability study was carried out to show the improved consistency obtained using the latest rig with the filter. Table 7.2 shows a summary of the repeatability tests carried out using the same slab of IAA 10/40. It can be seen that the filtered signal from Mk III results have a lower level of variability for the 20 drops compared to the unfiltered signal. Although the values of the peak g and the severity index are

reduced, the improved consistency provides a better method for comparing results from different materials. Using the unfiltered trace allows the energy lost due to the filter to be monitored.

Table 7.2 - A summary of results of a repeatability study carried out on Impact Attenuation Rigs Mk II and Mk III dropped 0.4m on IAA 10/40

Signal Trace	Mean Peak g	Standard Deviation, Peak g	Mean Severity Index	Standard Deviation, SI
Mk III, Filtered	110.8	2.9	260.9	9.3
Mk III, Unfiltered	126.6	9.5	338.4	17.7
Mk II, Filtered	112.1	4.54	269.8	16.7

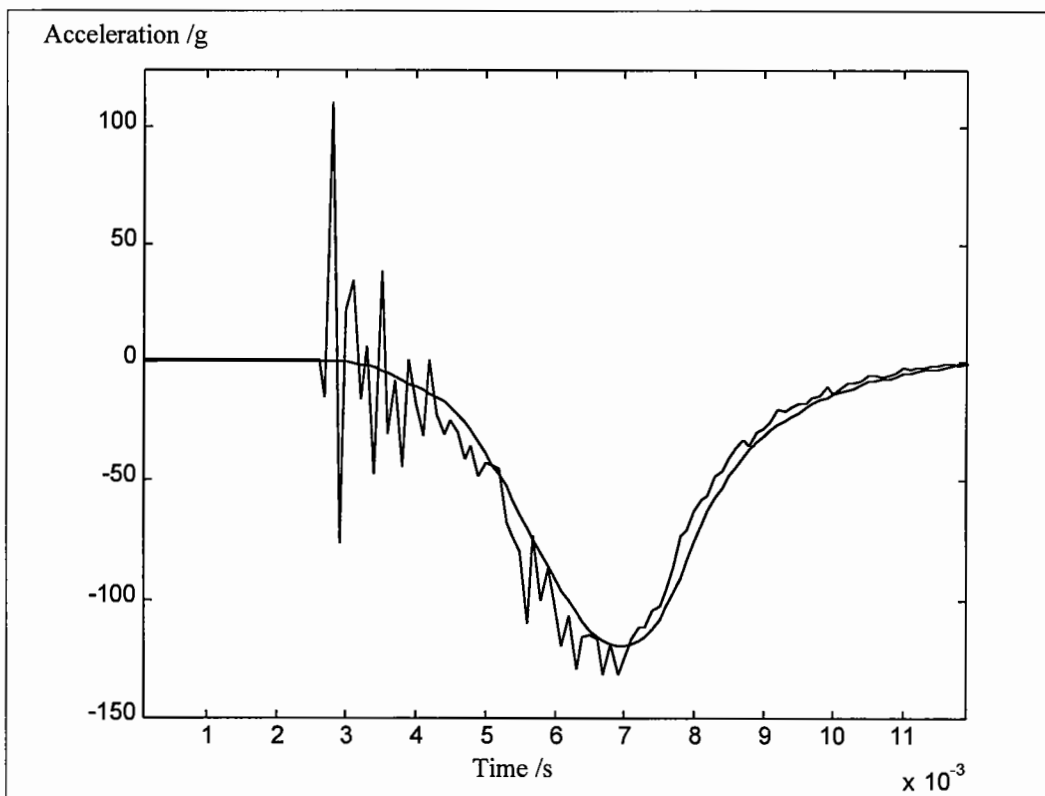


Figure 7.12 - A typical impact trace for IAA 10/40 from 0.4m using Impact Rig Mk III

The comparison between the second and third prototypes indicates that the latest design gives a higher consistency for measuring peak g and impact severity. This is probably due to the higher percentage of mass of the impactor being concentrated in the head form, thus reducing vibrations in the system, decreasing the energy loss and producing a more consistent pulse.

7.3.3 Development Summary

The previous sections have described the process carried out in developing the impact attenuation test so that it closely correlates to the impact of a spherical head form stipulated in BS EN 1177 but based on using an uni-axial accelerometer. It was the intention of this work to develop a test that was well controlled, simple and repeatable. The third prototype is well controlled by way of the guide poles that hold movement of the head form in the vertical plane and the test is relatively simple because of the few moving parts in contact with the impact mass resulting in a test with good repeatability.

7.3.4 Experimental Development

One of the main disadvantages of using guide poles to control the direction of drop over free fall is that the speed of drop is reduced by friction in the bearings. Therefore, the velocity at impact will be less than that expected if the drop was free fall. The British Standard test is a measure of free fall height against either peak g or severity index. Therefore, the velocity, or effective free fall height must be calculated for each drop.

The effect of friction in the bearings can be corrected for by calculating an ‘effective’ drop height corresponding to the actual velocity at impact using the following equation;

$$h_{eff} = \frac{v^2}{2g} \quad 7.5$$

where;

h_{eff} = Effective drop height

- v = velocity at impact
g = Acceleration due to gravity, $g= 9.81\text{m/s}^2$

Using the Impact Attenuation Test at the University of Nottingham the effective drop height was estimated using the time taken from release of the head form to the point at initial impact. The bomb release mechanism is used to release the head form and bar for the drop to commence. It provides a clean release without altering the direction of drop. A pulse, from the bomb release mechanism, on the accelerometer trace indicates the start of the drop and the end of the drop is taken to be the start of the impact trace. The actual drop height was measured and an average acceleration was calculated using the following equation;

$$a_{av} = \frac{2s}{t^2} \quad 7.6$$

where;

- a_{av} = average acceleration of head form during drop
s = actual drop height
t = time taken for drop

In a frictionless system the mass will accelerate at a rate of 1g as it falls. Therefore, a system with friction will be slowed down and accelerate at some fraction of 1g. The ‘effective’ drop height can then be calculated using the following equation;

$$H_{eff} = \frac{a_{av}s}{g} = \frac{2s^2}{t^2g} \quad 7.7$$

where:

- H_{eff} = Effective drop height

This method has been found to be the most successful for estimating the effective drop height. However, it assumes that the head form drops with a constant acceleration. This may not be the case because the friction in the bearings may not be consistent. An image analysis processor was used to confirm that this method provides the best estimate for the effective drop height. This also provided a method to closely observe the impact and assess if any problems were present.

Validation

The image analysis processor comprises a digital video camera that has the facility of recording images up to a rate of 1000 frames per second. The camera was set up on a tripod and recorded frames as the head form impacted the surface. A schematic of the layout is shown in Figure 7.13. The frames were stored, digitised and transferred to a computer so that measurements could be made from each frame. Using a simple scale, the measurements taken from the computer were normalised to give the actual distances as the head form moved through each frame.

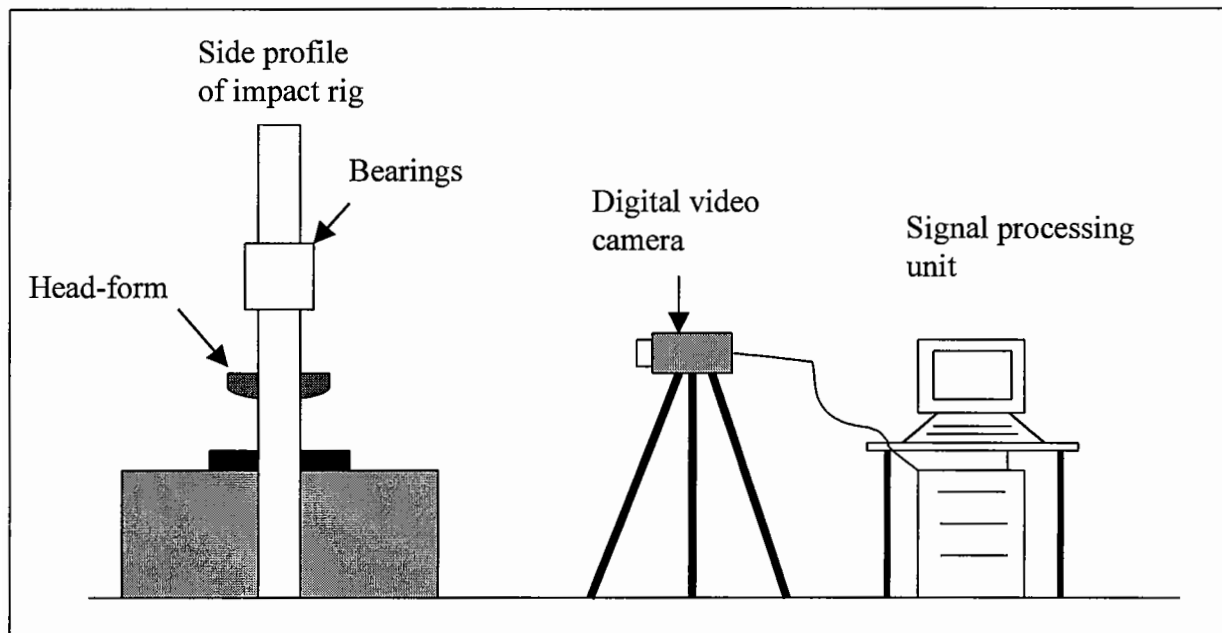


Figure 7.13 - A schematic of the image processor layout for the impact rig

Using this method, the impact velocity, the depth of impact, the rebound velocity and the rebound height, were estimated. Figure 7.14 shows a graph of the measurements taken from the image analysis equipment for a drop from a height of 0.2m. The measurements taken just before the contact are used to calculate the impact velocity. The depth of penetration and rebound height can be measured directly from the graph, and the rebound velocity can be calculated from the measurements taken as the head form leaves the surface.

For each drop monitored, data was collected from the accelerometer to enable comparison of the impact velocity, time of impact and rebound velocity. This is to

confirm that the impact velocity and rebound velocity calculated by integrating the acceleration trace were accurate. Firstly, the effective drop heights were compared as this is critical for plotting peak deceleration and Severity Index (SI) traces. The problem with timing the drop using the accelerometer trace is that there is only a slight change in the acceleration when the head form is released. Therefore, it is difficult to interpret accurately, the time at which the drop starts. This method also assumes that the head form accelerates at a constant rate. The image analysis was used to confirm the effective drop height calculated from the accelerometer trace by measuring the impact velocity which is measured from the gradient of the distance-time curve immediately before the head form contacts the surface.

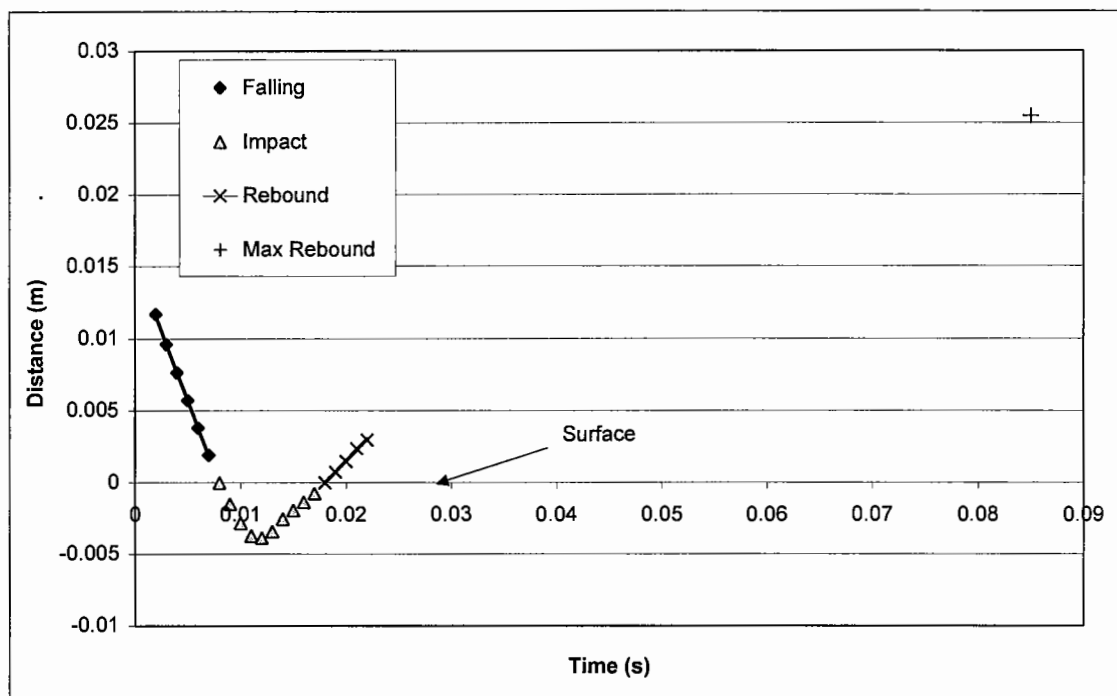


Figure 7.14 - Vertical movement of the head form as it impacts the surface

Figure 7.15 shows a graph of effective drop height versus actual drop height from the two methods. It can be seen from this graph that there is very little difference between the effective drop heights measured using the two methods. This reaffirms that the method of timing the drop is valid for measuring the effective drop height. Also illustrated in this figure is a line representing free-fall of the head form; the bearings and air provide resistance for the impact test at the University of Nottingham, slowing the head form down, which is why calculation of the effective drop height is necessary. The results have shown that the effective drop height is approximately 95% of the actual drop height.

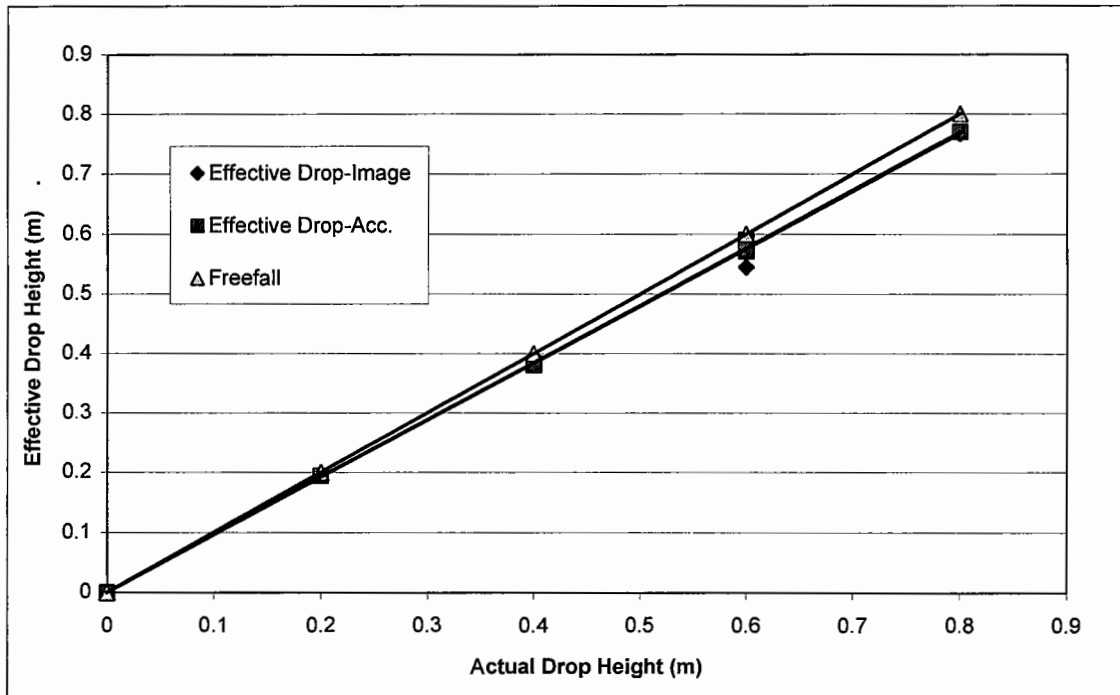


Figure 7.15 - Difference between two methods of calculating the effective drop height

The acceleration trace can also be used to estimate the coefficient of restitution. The coefficient of restitution is used as a measure of the energy absorbed due to the impact between the two surfaces.

$$e = \frac{v_{reb}}{v_{imp}} = \frac{(h_{reb})^2}{(h_{eff})^2} \quad 7.8$$

where;

- e = coefficient of restitution
- v_{reb} = rebound velocity
- v_{imp} = impact velocity
- h_{reb} = effective rebound height
- h_{eff} = effective drop height

The image analysis method is ideal for measuring the coefficient of restitution as the rebound height can be measured accurately. The initial method, using the accelerometer, involves integrating the acceleration trace during impact, to calculate the rebound velocity. The impact velocity was calculated using the effective drop height and acceleration due to free-fall (i.e. 1g). Therefore, the coefficient of

restitution is simply the ratio of the two velocities. The image analysis method for calculating the coefficient of restitution used the measured rebound height divided by the effective drop height calculated from the impact velocity measured from the image processor and therefore is more accurate. Figure 7.16 illustrates the values compared.

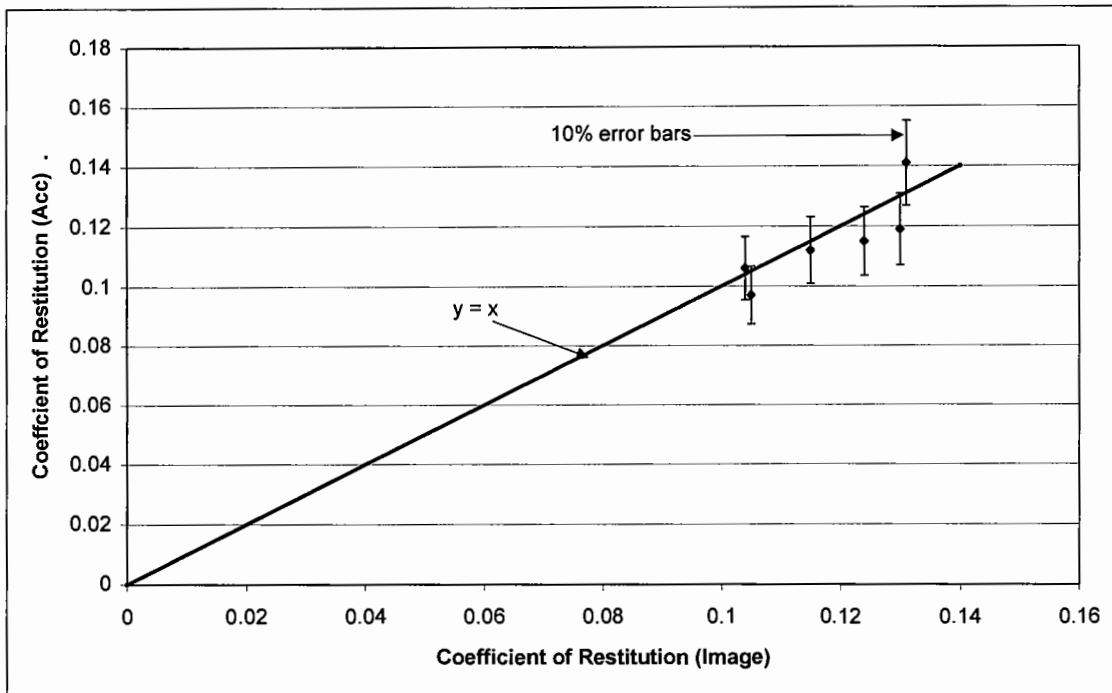


Figure 7.16 - Comparison between the 2 methods of calculating the coefficient of restitution

The graph above shows the coefficient of restitution calculated using the accelerometer on the y-axis and the coefficient of restitution calculated with the image analysis equipment on the x-axis. The graph indicates that the two values are within +/-10% of each other. The error bars are simply applied to results on the graph so that they cross the $y=x$ line where the two methods would give the same values. The coefficient of restitution calculated using the accelerometer provides a close indication of the energy absorbed by the impact. A perfectly elastic impact would give a coefficient of restitution of 1, illustrating that the all the energy of the impact is returned to the impactor, resulting in it rebounding at the impact velocity. These values of coefficient of restitution are low and indicate that only 10% of the energy is returned to the impactor, suggesting that 90% of the impact is absorbed in the surface and impact system.

The image analysis processor has provided confirmation that the effective drop height is accurately measured using the data from the accelerometer trace. It has also suggested that the coefficient of restitution can be measured by integrating the impact trace to within an accuracy of +/-10%.

7.4 Sub-base Measurements

Conventionally, IAA is laid on a granular sub base material when it is used as the shock pad layer for an artificial turf pitch. Impact tests carried out on the material in-situ have indicated that the measured impact severity is lower in the field than in the laboratory. It is thought that one of the reasons for this is the difference in stiffness of the sub base materials. The tests carried out in accordance with BS EN 1177 (1998) are on a specimen placed directly on a concrete base which is significantly stiffer (40,000MPa) than a typical compacted granular type 1 sub base (250MPa). Therefore, if the sub base material has an affect on the impact results the concrete will cause larger values of peak deceleration and severity indices for the tests carried out in the laboratory. The initial task is to assess the load applied through to the sub base on each impact. The effect of changing the sub base stiffness on the impact severity will be investigated in Chapter 8.

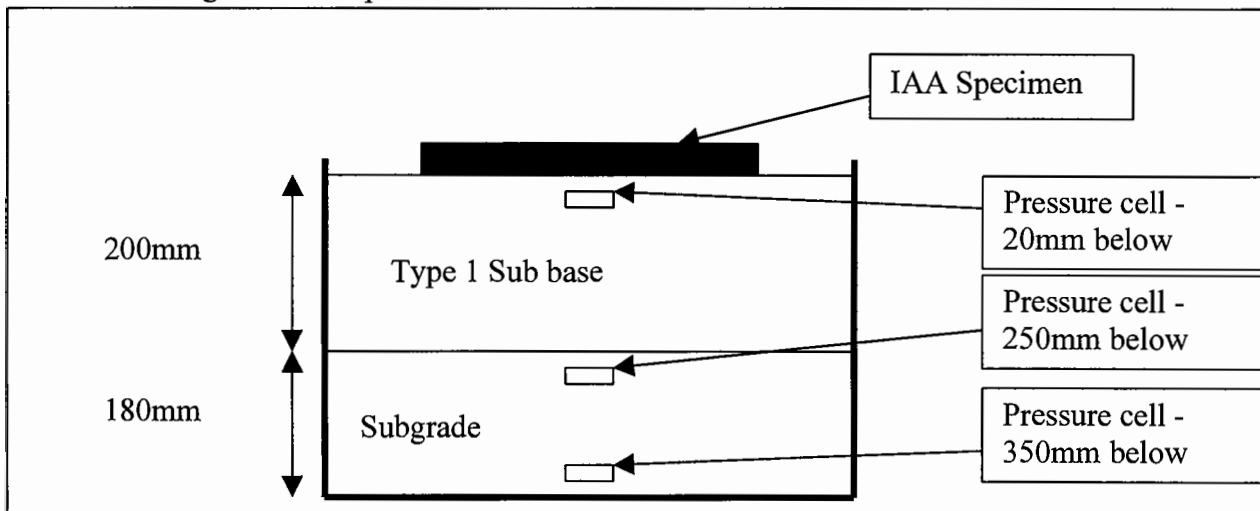


Figure 7.17 - Schematic of the sub base box constructed to investigate the effect of the sub base on impact results

Figure 7.17 shows a box constructed to simulate a typical layered pavement substrate with subgrade and sub base material. Pressure cells were placed at different depths of the box to measure the depth and area of influence from an impact. The pressure cells are used to indicate the significance of the sub base material and also measure the area

of influence underneath each impact to check that the size of the box and the specimen are sufficiently large.

Figure 7.18 illustrates the accelerometer traces (negative y axis) and the pressure cell traces (positive y axis) from directly under the impact point. The pressures recorded directly underneath the impact are expected to be the most significant values in the sub base.

To compare how the pressure is reduced with depth below the surface the peak pressure on the surface of the IAA can be calculated using an estimated contact area. For this impact the maximum contact pressure is in the region of 1700kPa. The maximum pressure underneath the IAA specimen (20mm below the surface) is around 260kPa. Indicating a reduction in stress in the order of 85%. Using the same method the reduction of stress at 250mm is 98% and for 350mm below the surface the reduction is 99%. The effect of the sub base is therefore found to be significant because some of the load from the impact is clearly transferred.

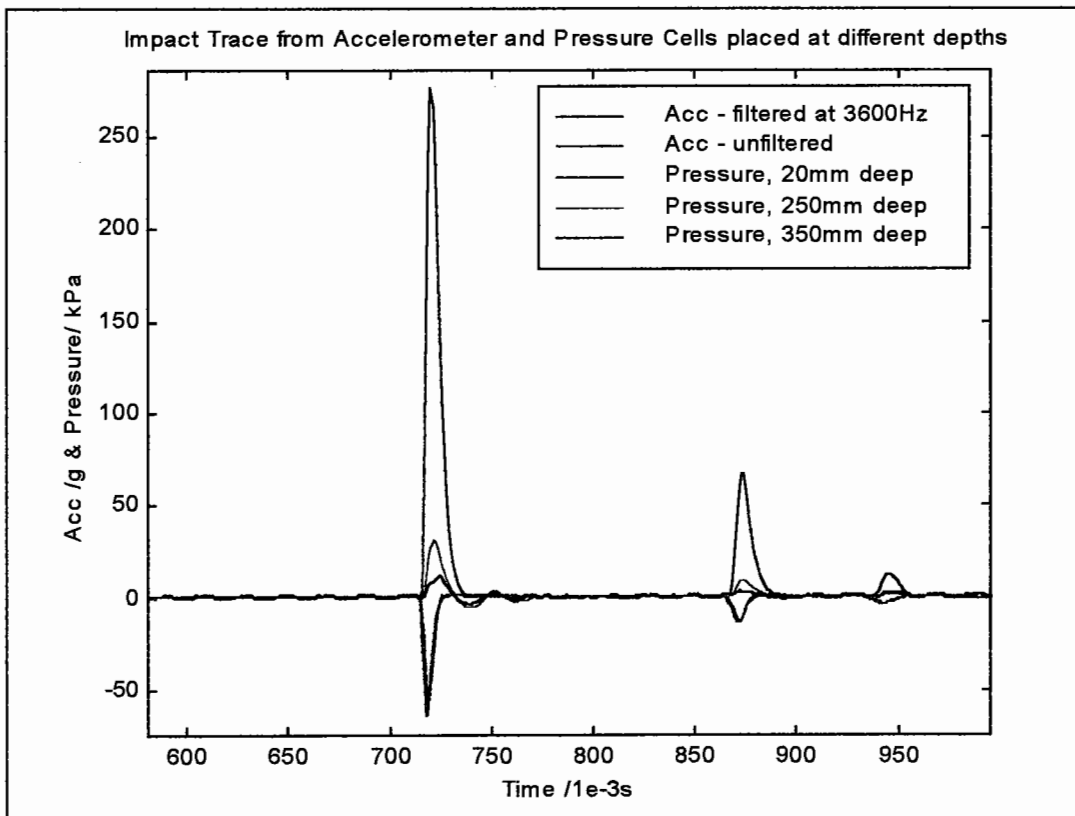


Figure 7.18 - Accelerometer and pressure cell readings from an impact of a 0.2m drop

The further peaks along the time axis represent the impact head bouncing on the surface. The area of influence was measured by moving the impact point radially away from the line of pressure cells. The maximum pressure was used as a reference, but it should be noted that it does not occur at the same time as the peak deceleration. This is due to the time lag that takes place as the pressure is applied to the surfaces underneath, i.e the pressure wave initiated by the impact takes time to pass through the IAA. Figure 7.19 illustrates the area of influence at each of the depths where the pressure cells were located. The impact point was moved so that the pressure cells could measure what load is transferred radially outwards. This would indicate if the slabs being tested are large enough to absorb the pressure waves transmitted sideways from the impact.

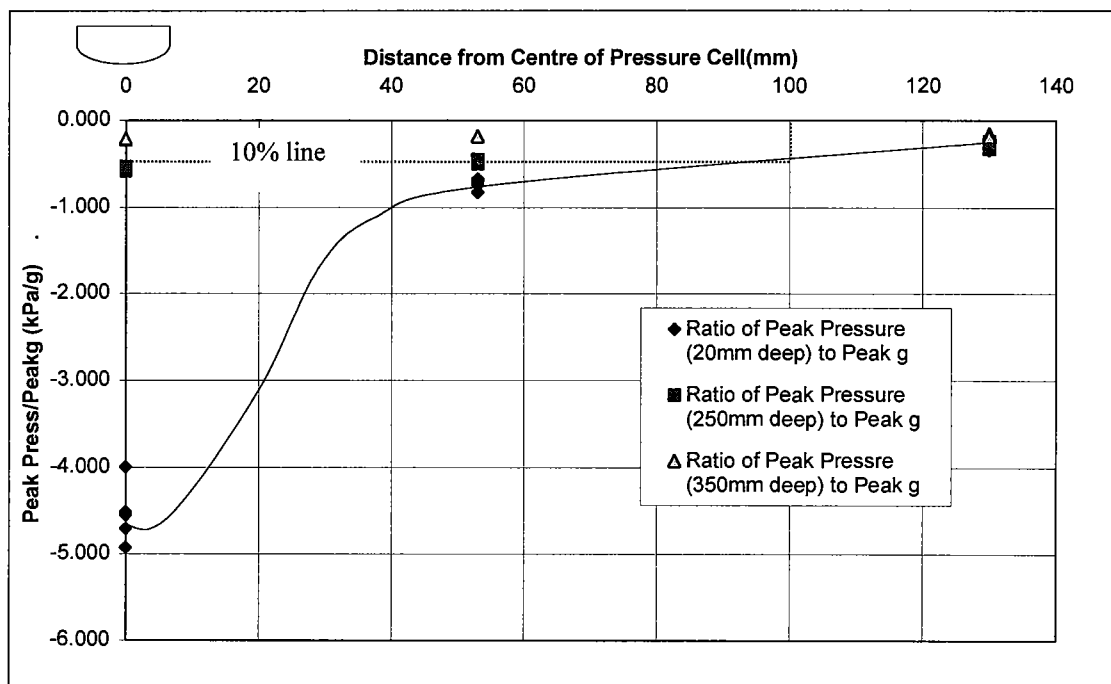


Figure 7.19 - Area of influence underneath a slab of IAA 10/40

It can be seen from Figure 7.19 that the maximum pressure directly underneath the specimen decreases fairly rapidly radially. Within 100mm of the impact point, the pressure has decreased to about 10% of the maximum central value.

In summary, the pressure cells in the sub base box have shown that the sub base material does have an influence on the impact severity. Therefore, the next stage is to quantify this influence so that a surface material can be designed to be placed on a known sub base with known properties. The test results have also shown that the area

of influence in the IAA specimen is predominantly within a 100mm radius of the impact point. Therefore, it is reasonable to continue to test the slabs made in the roller compactor that measure 404mm x 280mm ensuring the impact points are kept within 100mm of the edge.

7.5 Summary and Conclusions

This chapter has described the impact testing of impact absorbing surfaces for specific use on sports surfaces and playgrounds. The types of impact tests have been described, the advantages and disadvantages have been outlined concluding that the impact attenuation test is the most suitable to use on Impact Absorbing Asphalt as a performance test for sports and playground surfaces.

The development of the impact attenuation test at the University of Nottingham has been described. An uni-axial accelerometer was used instead of a tri-axial accelerometer as recommended in the standard testing procedure. Therefore, a guidance system was required to control the direction of the drop. Problems associated with this system were overcome through a series of prototypes and a test procedure was developed to account for the reduction in impact velocity due to friction in the guidance system.

The load transferred through to the sub base upon impact of slabs was measured to assess if the stiffness of sub base was important to the impact results on the slab. This was found to be the case and an investigation was carried out to assess the effect and will be detailed in Chapter 8. Assessment of the sub base loads was also carried out to find the area of influence of each impact. Therefore, the area of influence in the slab is known which gives an indication of the minimum dimensions of material required for each impact.

The development of the equipment and test procedure has enabled a test protocol to be developed that can confidently assess the impact absorbing characteristics of a material.

8. IMPACT ATTENUATION TESTS ON IMPACT ABSORBING ASPHALT

8.1 Impact Test Standards

8.1.1 Playground Surfaces

The safety standard defined by the European standard EN 1177 (1998) uses the impact attenuation test to determine the critical fall height on to a surface. Critical fall height is the effective drop height where Head Injury Criterion (HIC) or Severity Index surpasses a value of 1000. As discussed in Chapter 7, the value of 1000 represents a frontal head impact that would provide a fatal blow. To determine the critical fall height of a surface material a number of drops of the impact attenuation test are required at different heights. The severity index is then calculated for each drop and plotted against the effective drop height. The effective drop height is the height the impactor is started from assuming no losses through the fall (i.e. free fall). The plot of severity index against effective drop height is then fitted with a line of best fit and the point at which it passes the SI value of 1000 is deemed the critical fall height for that material under the given conditions.

The critical fall height represents the height of allowable fall on the surface. For example, for playgrounds without equipment the maximum fall without restraint (i.e. hands and knees used to break fall before head hits the surface) is around 0.6m. Therefore, the critical fall height for an impact absorbing surface material should be greater than 0.6m.

8.1.2 Sports Surfaces

Impact absorption is a major performance characteristic for sports surfaces as it relates to the way the material will interact with the user and the reduction of potential injury through falling or use. The impact attenuation test is a European standard and has been adopted by a number of sporting bodies as a major test for the performance of sports surfaces. The Sports Council in the UK have established the test to measure peak deceleration as a general "club standard" to be less than 200g from an effective drop height of 1m. The British Standard 7044: Part 4 (1990) also uses this as a limiting performance of general sports surfaces. The Football League Committee of Enquiry state that for surfaces used in Football League matches the peak g must be

less than 225g from an effective drop height of 1.5m. These values refer to the performance of the material when laid in-situ and accounts for the whole layered system including sub base, base and surface materials as one unit. IAA 10/40 provides the shock absorbing layer in the base, so testing on IAA 10/40 alone does not represent how the material will perform when part of the layered system. The effect of the sub base and the surface layer will be characterised later in the chapter.

8.2 Impact Testing 3/20

8.2.1 Method

A number of specimens were made with different mixture designs, short term ageing and under different conditions to assess their effect on the impact performance of the material. The intended purpose of IAA 3/20 is to provide a shock absorbing surface for playgrounds in schools. It is not designed to be placed around playground apparatus such as swings and climbing frames where the possible drop height is greater than 0.6m. Therefore, the critical fall height the material must be designed to is 0.6m where the severity index is less than 1000.

Impact testing was carried out in the impact attenuation test at the University of Nottingham on the updated Mark III equipment. IAA 3/20 is designed to over lay an existing bituminous pavement surface, so to simulate typical foundation conditions each slab of 3/20 was placed on a slab of a conventional bituminous wearing course which was laid on a compacted sub base box.

The slabs produced in the laboratory were compacted using a roller compactor in a mould measuring 280mm x 404mm. The European standard states that the minimum dimensions for a test specimen is 1m x 1m to fully represent the performance of the material in-situ. However, initial testing using pressure cells underneath the slab showed that the impact load is spread only 100mm away from the impact load. Therefore, the testing of the laboratory made slabs in the impact attenuation test was judged satisfactory as long as the impact point was at least 100mm from the edge of the slab.

The procedure of testing adopted was developed through experience and repeatability studies. The slab was laid over a 40mm thick bituminous slab that was bedded into the sub base with sand. The impact point was marked and the impactor then raised to a predetermined height. The impactor was then dropped and the acceleration-time trace was recorded. The sub base box, with the two slabs on, was then moved so that the impact point was at least 50mm from the previous point on the slab. The impactor was then raised to the same height and dropped again, recording the acceleration-time trace. The same drop height was repeated a total of three times on three different points on the slab so that the slight damage caused by the impact did not affect further results. The drop height was then increased and the same procedure repeated.

The acceleration-time trace was collected via a uni-axial accelerometer fixed to the head form and measured in units of g. The sample rate was 10kHz and an external low-pass filter was used to filter the data at 3.6kHz. A high-pass filter was used at 0.03Hz to ensure that the trace did not drift from the datum. The low pass filter was used to smooth the impact trace by reducing high frequency noise in the signal. However, due to the way the filter works it also reduces some of the low frequency measurements that represent the impact trace. Although these losses are minor, it was deemed necessary to monitor the effect of the filter so a second channel was used to record the unfiltered trace. On the completion of testing, the acceleration-time traces were processed to calculate the effective drop height, the peak g and the severity index for each drop. The data were then collated and the severity index against effective drop height was plotted for each slab.

Four main parameters have been altered to investigate their effect on the impact performance of the 3/20 IAA. These were carried out in conjunction with the abrasive wear test to investigate the best performing mixture design for 3/20 IAA. Specimens with different proportions of rubber were made to assess the effect of rubber content on the impact absorbing performance of the material. Specimens were also made that contained the same rubber to aggregate proportions but altered the bitumen content, these were also tested for impact absorbing properties. The initial samples had been made in the laboratory, where the material is mixed, placed in an oven at 155°C for 1 hour to raise the mixture to an even temperature and then compacted. In the field, the material is mixed at the plant and then transported to the site where it is laid and

compacted. During the transportation period the material must be maintained at a sufficiently high temperature for the material to be workable when laid and compacted. Specimens were made that simulated this period to assess how short term ageing affects the impact performance of the material. Slabs were also made by using a conventional in-situ compaction method to compare the impact absorbing performance with the laboratory compacted specimens. Finally, a full scale in-situ trial was constructed and the impact attenuation test was made portable to enable on-site impact testing. The results are presented and compared to the laboratory and in-situ compacted samples.

8.2.2 Results

The procedure was to repeat the same drop height at three different points on the slab to give an indication of the variability of the test and the variability of the slab. It was found that the variability of the slab did not vary through the different mixture designs, ageing or compaction methods. This ensured that the results all had a similar repeatability associated with them. It was also found that the low pass filter reduced the value of the SI by approximately 10%. This figure was not consistent for each drop because the vibrations picked up by the unfiltered trace altered the SI value. Therefore, to provide better repeatability, the filtered trace was monitored and used to measure the SI value for each drop.

Effect of rubber content

The rubber content in the mixture design of IAA 3/20 was altered to investigate the change in impact performance due to the rubber content. Slabs were made and compacted in the laboratory using the method described in Chapter 6 that had 15%, 10%, 5%, 2.5% and 0% rubber content by mass of the total mixture and were 20mm thick. The slabs were then conditioned at 20°C for 2 hours before testing in the impact attenuation test. The slabs with 15%, 10% and 5% rubber were tested up to a height of 0.45m to avoid permanent damage to the material so that further testing could be carried out on the samples. The data was then extrapolated using a line of best fit to find the critical fall height of the material. The results are presented in Figure 8.1.

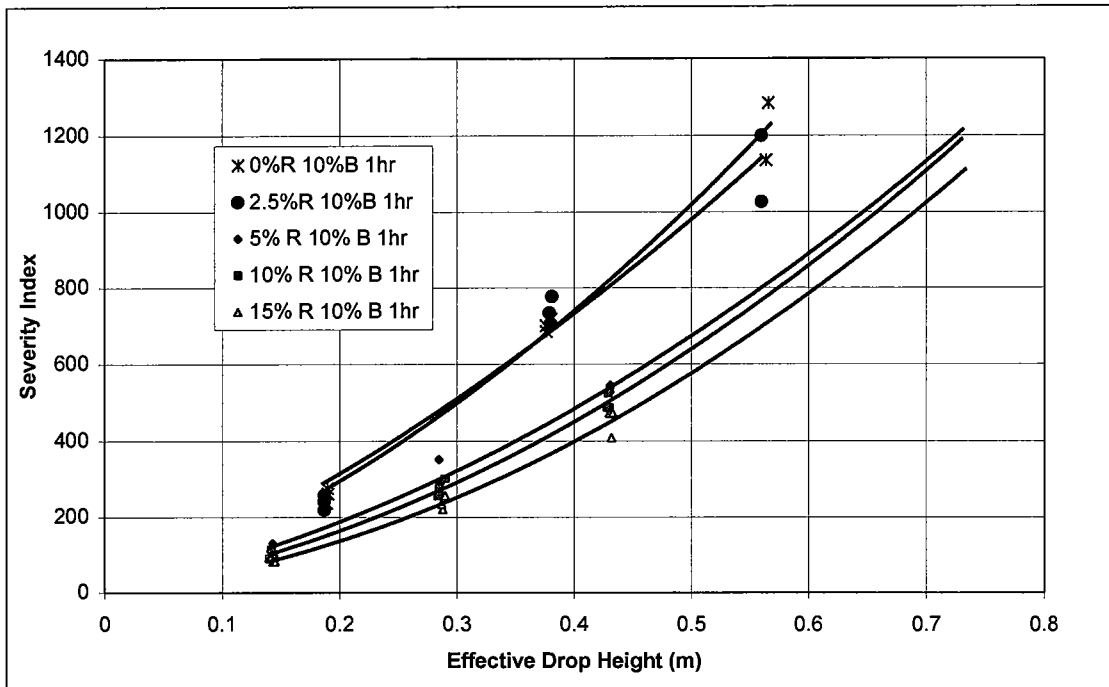


Figure 8.1 - Severity Index against effective drop height for IAA 3/20 with different rubber contents short term aged for 1 hour

The results show that the increase in rubber content reduces the impact severity of the material. This is illustrated if the severity index at a drop height of 0.6m is plotted against the rubber content in the material.

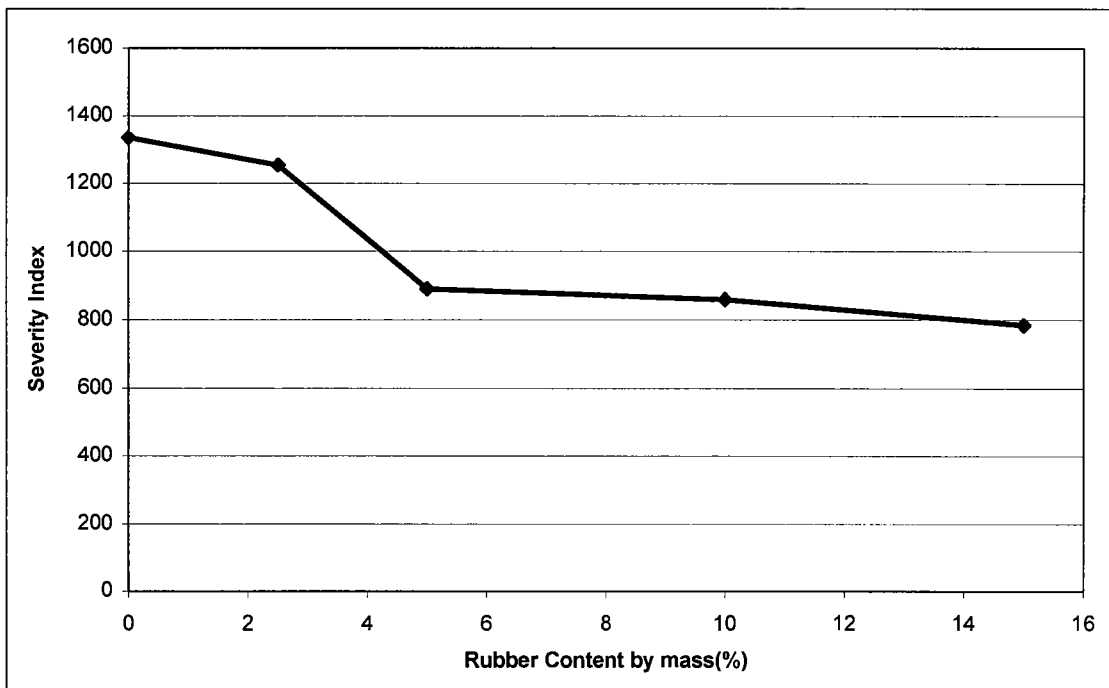


Figure 8.2 - Severity Index for a drop height of 0.6m for laboratory compacted 3/20 IAA with different rubber contents short term aged for 1 hour

Figure 8.2 shows that if the rubber content in the 3/20 mixture is 5% or greater, the severity index is less than 1000 for a drop from 0.6m. The two slabs tested with 0 and 2.5% rubber show very little difference in severity index, suggesting that a small amount of rubber does not improve the impact absorbing characteristics of a conventional bituminous material. However, when the rubber content is 5%, the severity index is decreased significantly and does not significantly decrease as the rubber content is increased more.

Effect of bitumen content

The investigation of mechanical durability showed that an increase in the bitumen content in the mixture improved the ability of the material to resist abrasive wear. To measure how this factor affects the impact absorbing characteristics, slabs were made and compacted in the laboratory with different bitumen contents and tested in the impact attenuation test. The results are presented in Figure 8.3 and show only a small variation in the impact absorbing characteristics of 10%, 12.5% and 15% bitumen. Despite the slabs containing slightly less rubber in terms of mass and volume, the increase in bitumen does not appear to stiffen the material significantly and thus reduce the impact absorbing characteristics.

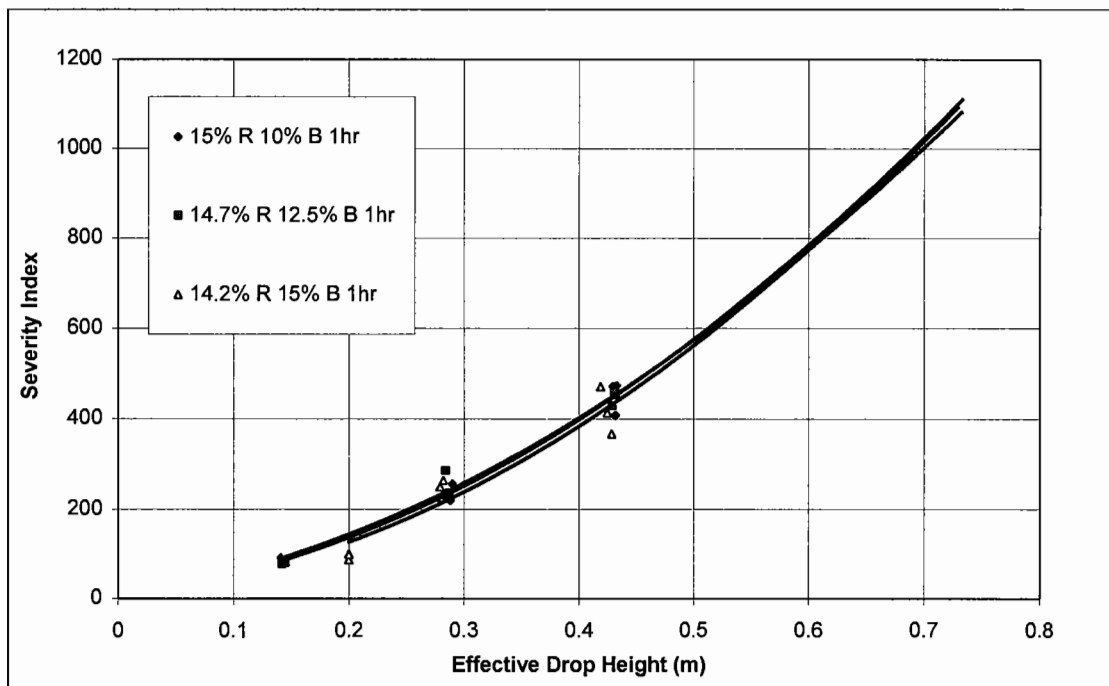


Figure 8.3- Severity Index against effective drop height for IAA 3/20 with different bitumen contents short term aged for 1 hour

Effect of short term ageing

The specimens that were short term aged for the Abrasive Wear Test were tested in the impact attenuation test to investigate what effect the interaction between the rubber and the bitumen had on the impact absorbing characteristics of the material. The originally developed mixture containing 10% Bitumen and 15% rubber by mass was aged for 1, 6 and 24 hours. The specimens were then compacted in the laboratory, allowed to cool and tested in the impact attenuation test prior to being tested to destruction in the abrasive wear rig. The results are presented in Figure 8.4 and show that the short term ageing does alter the impact absorbing characteristics. The 6 hour aged specimen increases the impact severity over the 1 hour aged specimen, indicating an increase in stiffness of the material as it is aged. However, a further increase in ageing to 24 hours appears to reduce the impact severity. This is due to the degree of compaction of the samples. As indicated in the results from the abrasive wear test, the density of the specimens are a good indication of the degree of compaction of the specimens.

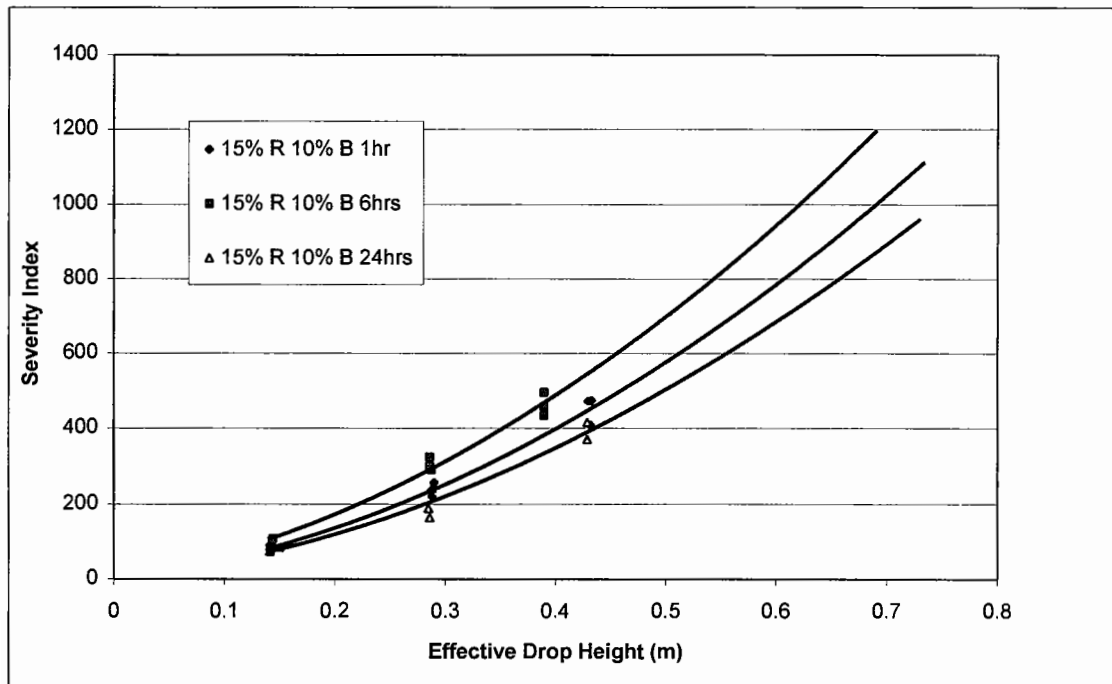


Figure 8.4 - Severity index against effective drop height for different short term aged specimens of IAA 3/20

Table 8.1 - Summary of specimen densities

Specimen	15% R 10% B, 1hr	15% R 10% B, 6hrs	15% R 10% B, 24hrs
Density (kg/m ³)x10 ³	1.61	1.65	1.55

The table above shows that the density of the 6 hours specimen is greater than the 1 hour, which in turn is greater than the 24 hour aged specimen. The specimens were compacted in the laboratory so that the same procedure and temperature for compaction were used and the same compactive effort was made on each specimen. Therefore, the difference in density is due to the change in the mixture workability. As indicated in the durability chapter the interaction between the rubber and the bitumen at high temperatures for the 6 hour aged specimen increases the stiffness of the bitumen, reducing the amount of rebound after cooling. Therefore, the material can be compacted to a higher degree and will be so as long as there is still sufficient bitumen available to bind the rubber and aggregate together. The 24 hour aged specimen is likely to compact poorly because there is very little bitumen in the mixture having mainly been absorbed by the rubber. Therefore, the material will not bind very well and will not be compacted very well thus increasing the impact absorption and reducing the impact severity.

The density of the specimen appears to be the controlling factor for the way the material performs as an impact absorbing layer. Testing of the actual rubber particles showed a decrease in stiffness of the rubber due to it absorbing fractions of the bitumen but this does not appear to be a major factor in the impact performance of the material. There is also the argument that the increase in the stiffness of the bitumen through the interaction with the rubber will increase the severity of the impact. However, the governing factor appears to be the level of compaction according to the workability of the mixture. This can be further illustrated by comparing different compaction methods by compacting the material in-situ.

Difference between in-situ and laboratory produced specimens

Up until now all the impact results have been on the specimens produced in the laboratory. It is important that if these results are useful they can be related to the performance of the material made in the field. It has already been mentioned that the production of laboratory specimens varies slightly from the material made in-situ. The main differences are in the methods of compaction used. Essentially, the laboratory specimens are 'held' down when compacted until the material is cool and the bitumen stiff enough to bind the rubber and aggregate together without much rebound. The in-situ compacted specimens are compacted using a roller and not 'held' until cooled. Therefore, the material can rebound while it is still hot and generally there is less compactive effort and the specimens are not as well compacted.

Figure 8.5 shows results on impact tests carried out on the in-situ compacted specimens. The main affect these results show is that the increase in rubber content decreases the severity index to a greater degree than the specimens compacted in the laboratory when the only difference between the specimens is the method by which they have been compacted. Figure 8.6 shows a comparison of severity index at 0.6m against rubber content between the in-situ and laboratory compacted specimens.

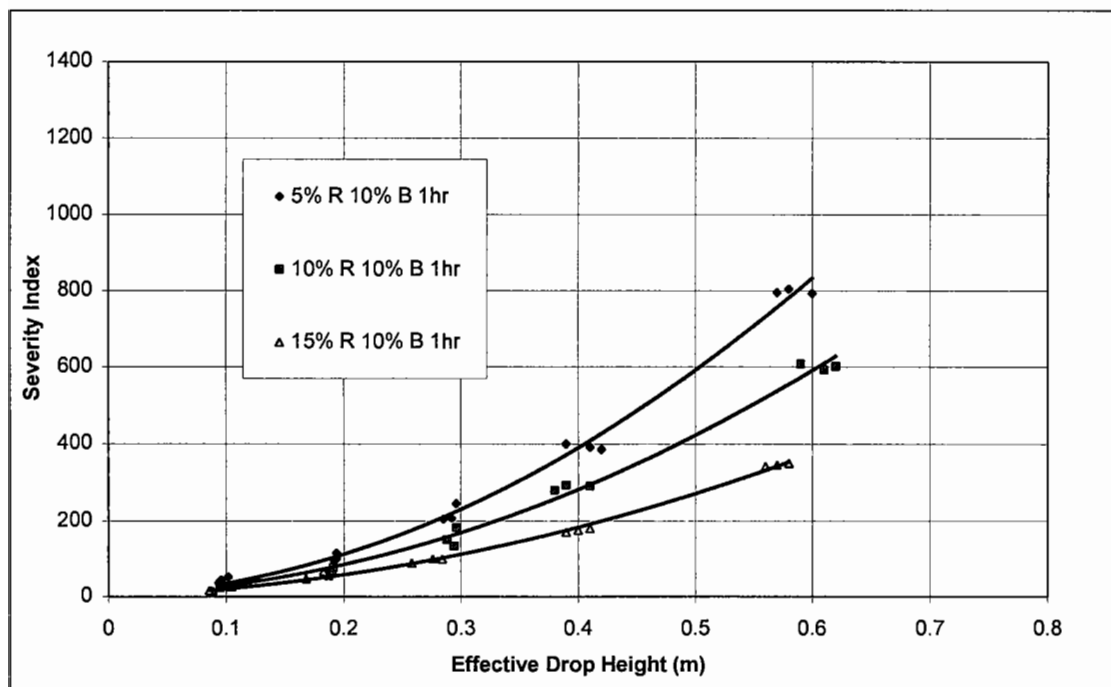


Figure 8.5 - Severity Index against effective drop height for in-situ compacted specimens of IAA 3/20

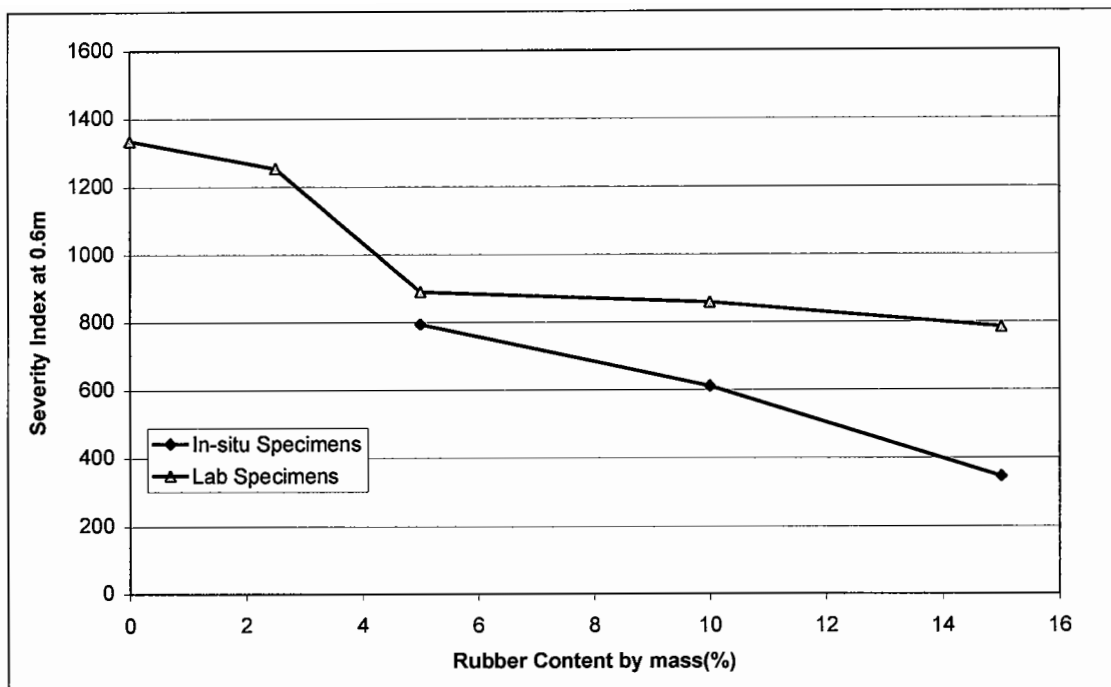


Figure 8.6 - Comparison of impact severity for in-situ and laboratory compacted specimens of 3/20 IAA

The main difference between the laboratory compacted specimens compared with the in-situ compacted specimens is that the laboratory compacted specimens produce a higher severity of impact. As the rubber content is increased the difference between the two production methods for impact severity is increased. This can be related to the fact that the rebound for the in-situ compacted specimens is greater due to the increase in rubber content and therefore the difference in relative densities is greater.

Figure 8.7 illustrates the severity index curves for a 0hr and 6hr short term aged slabs compacted using the in-situ method. This shows that as the material is aged, the impact severity is decreased. This is the opposite to what was found with the same materials for the laboratory compacted specimens (Figure 8.4), which illustrated that as the mixture was aged between 0 to 6hrs the severity of the impact increased. The increase was found to be because the density of the specimen aged for 6 hours was greater and thus the rubber was more constrained and less able to deform and absorb the impact. Again, the difference can be related to the densities of the specimen.

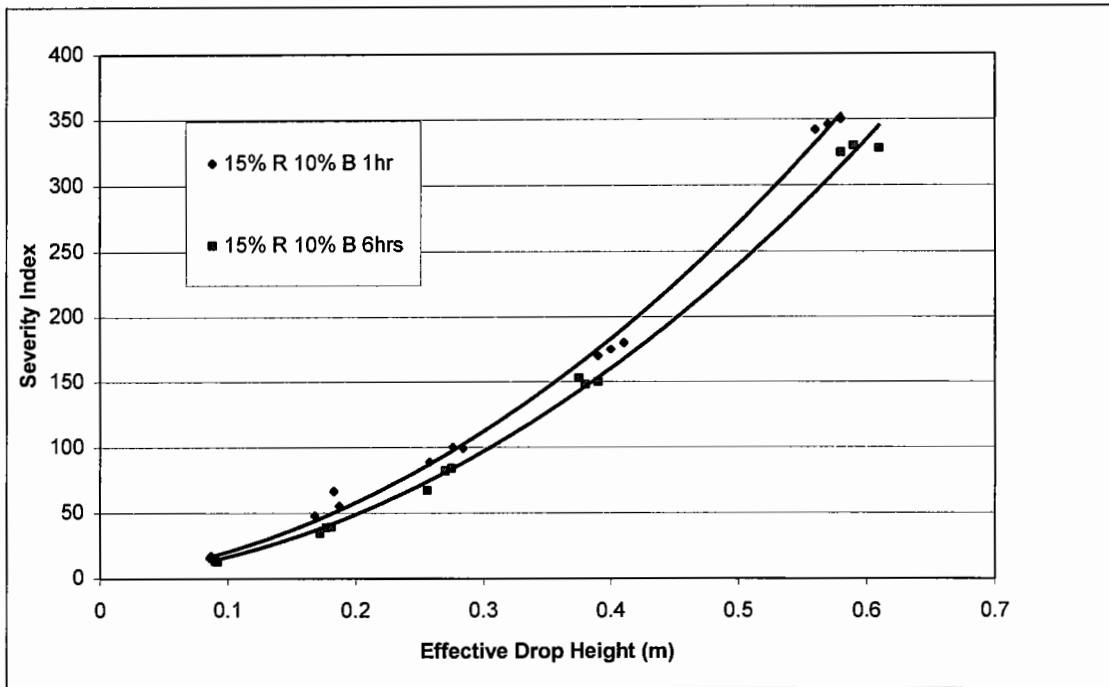


Figure 8.7 - Severity index against effective drop height for short term aged, in-situ compacted specimens of IAA 3/20

Table 8.2 shows the measured densities of the laboratory compacted specimens and the in-situ compacted specimens. As discussed in Chapter 6, the two methods produce different densities because the amount of compactive effort is greater for the laboratory specimens. The change of rubber content and short term ageing are compared.

Table 8.2 - Densities of in-situ and laboratory compacted specimens with different rubber contents and short term ageing

Specimen	Impact Severity at 0.6m			Density (kg/m ³)x10 ³		
	Laboratory Compacted	In-situ Compacted	Difference	Laboratory Compacted	In-situ Compacted	Difference
5% R, 1hrs aged	900	800	-100	1.88	1.87	-0.01
10% R, 1hrs aged	860	600	-160	1.75	1.63	-0.12
15% R, 1hrs aged	780	350	-430	1.61	1.55	-0.06
15% R, 6hrs aged	900	350	-550	1.65	1.50	-0.15

The relative densities of the specimens using the two compaction methods suggest that as the rubber content is increased the difference between the laboratory and in-situ compacted specimens is greater. This is caused by the fact that the in-situ

compacted specimens are allowed to rebound back more after compaction. Therefore, the increase in rubber content increases the amount the material bounces back and thus reduces the density of the material. This phenomenon manifests itself in the comparative impact severity of the specimens. As the density of the specimen is reduced through the different method of compaction, the impact severity also decreases. Also noticeable is the difference in short term ageing between the two compaction methods. These results show that as the density is increased the severity index at 0.6m is increased indicating that the density is the controlling factor for the impact performance of the material.

Relating in-situ measurements with laboratory

A full scale trial of IAA 3/20 was constructed in March 1999 at Lilybank Nursery School in Matlock, Derbyshire. Approximately 140m² of IAA 3/20 with 15% rubber and 10% bitumen by mass was mixed at a Kevin Quarry, approximately 20 miles away, transported to site and hand-laid to a thickness of 20mm over the existing bituminous pavement wearing course in the playground of the school. Construction was successful and one week after construction impact testing was carried out using a portable version of the impact attenuation test.

The material used at the trial was aged for a period of approximately 4 hours between mixing and laying while being transported. Therefore, as a close approximation, the laboratory measurements are given of IAA 3/20 that has been aged for 6 hours. The results are presented in Figure 8.8 along with the comparisons of both laboratory produced specimens; laboratory and in-situ compacted.

The results give an indication that the in-situ compacted specimen that was then tested in the laboratory in the impact attenuation test is a comparable material to the in-situ produced material at Matlock.

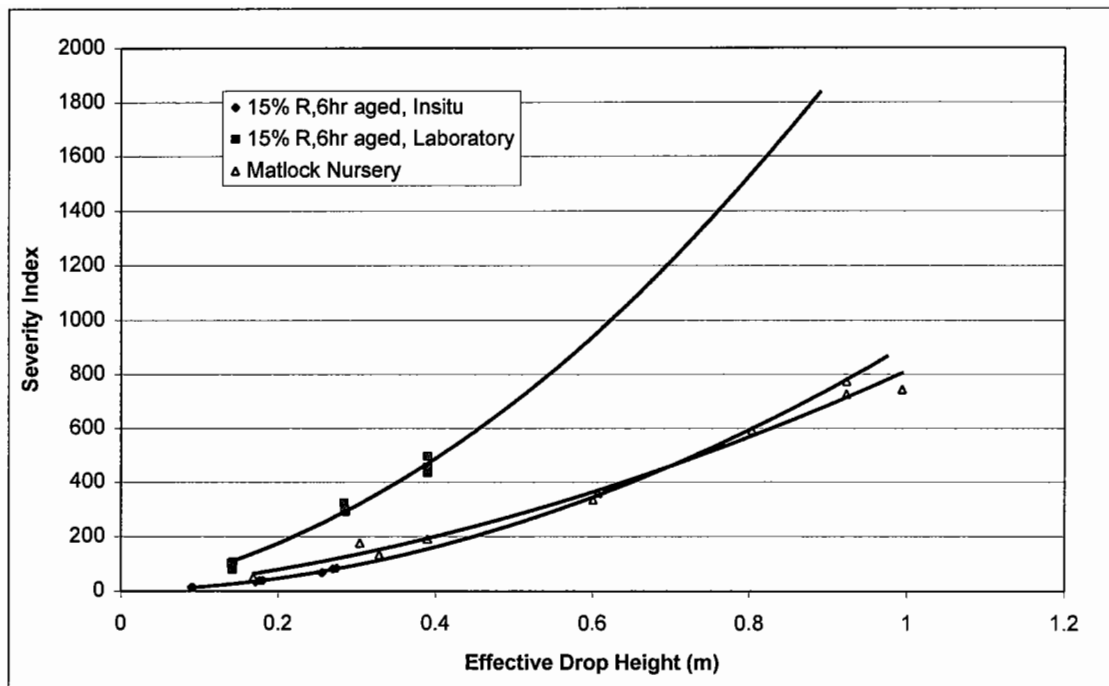


Figure 8.8 - Comparison between laboratory and in-situ measurements of IAA

3/20

8.2.3 Discussion

These results have shown two basic trends; an increase in compaction of the material increases the impact severity of the material and an increase in rubber decreases the impact severity. The bitumen content does not significantly affect the impact absorbing properties. The actual mechanics of these changes can be quite complex. Essentially, when the material is compacted in-situ the densities are lower than if it were compacted in the laboratory. This is because the laboratory specimens are held down with a dead load until they are cooled. Therefore, the rubber and aggregate matrix is compressed together until the bitumen is cool and stiff enough to hold it in. The in-situ compacted material is not held down with a dead load and the aggregate-rubber matrix is able to expand while the bitumen is still hot and fluid.

The compressed aggregate-rubber matrix for the laboratory compacted specimens has lower impact absorbing properties because it is restrained and is less able to deform under an impact. The less compacted in-situ produced specimens have a less restrained rubber-aggregate matrix and are more able to deform and absorb the impact.

This is also illustrated in the short term aged specimens that have different densities due to the change in workability of the mixture. Ageing of the material at 155°C increases the stiffness of the bitumen and thus reduces the amount of rebound of the material when the dead load is released. This is illustrated by the increase in density of the material as it is short term aged over 6 hours. The laboratory compacted specimens show an increase in density and consequently an increase in impact severity. However, as the material is aged for a longer period, more of the bitumen is absorbed by the rubber in the material, the available bitumen is reduced and thus the mixture is less workable and is not compacted as well. Therefore, the 24 hour short term aged specimen is compacted to a lower density and consequently has a lower impact severity.

The increase in rubber content in the mixture generally reduces the impact severity. However, the increase past 5% rubber does not significantly change the impact severity for the laboratory compacted specimens, suggesting that the extra rubber particles in the mixture are not utilised in absorbing the impact. The reason for this is not fully understood, but it may be related to the function of the rubber in the aggregate-rubber matrix and the compaction of the material. As already discussed, the material is held down by a dead load when it is compacted in the laboratory. If it was not, the material would rebound, as shown by the in-situ compacted specimens. Therefore, the rubber in the laboratory compacted specimens is restrained by the bitumen and aggregate and cannot deform and absorb the energy from the impact and an increase in rubber content has little effect on the impact absorption. Alternatively, the in-situ compacted specimens do show a change in the impact severity as the rubber content is increased because the material is allowed to rebound and the rubber is not restrained.

The method of compaction of the material in the field is usually going to allow the material to rebound and thus the rubber will not be restrained. However, this will lead to problems of durability because the material matrix will be poorly compacted. The density of the 5% rubber specimens does not alter for either of the two methods of compaction used. This suggests that the material does not rebound much and the rubber in it is not restrained. Therefore, the rubber in the material is optimised as an

elastomeric media for absorbing the impact and also the material can be well compacted because the material does not rebound much.

8.3 Impact testing 10/40

8.3.1 Method

As already mentioned, IAA 10/40 is designed to be used as the shock absorbing layer for sand filled artificial sports turf. The impact absorbing properties of the total system must be measured to see if the material will satisfy the requirements set by different sporting bodies. However, the initial aim of this work is to investigate how different conditions affect the performance of IAA 10/40. It was chosen to carry out impact testing under controlled conditions in the laboratory and then relate these to the performance of the system in-situ by separately investigating the effect of the sub base material and the surface carpet.

The test method for measuring the impact absorbing performance of IAA 10/40 material is similar to the method described for IAA 3/20 except that the peak g is recorded instead of the severity index. Testing to investigate the change in rubber content and change in test temperature was carried out on a solid concrete base. The investigations into the effects of the material depth, sub base and surface material was then carried out on purposely built sub base boxes that were ranked according to their effective stiffnesses under an impact.

8.3.2 Results

Effect of test temperature

The impact absorbing characteristics were measured at three different temperatures to assess what effect the temperature of the material had on the impact severity. The material used was IAA 10/40 with 29% rubber and 9% bitumen by mass. Testing was carried out by conditioning three slabs of the same mixture design at each test temperature (5, 20 and 35°C) for 2 hours. The slabs were then removed from the temperature controlled cabinet, placed on a concrete slab that is at ambient temperature and tested in the impact attenuation test immediately. The average temperature of the slabs was monitored using three temperature probes placed at the

bottom, the middle and the top of each slab. When the temperature of the slab differed from the original by more than 2°C, the test was stopped and the specimen placed back in the temperature control cabinet until it was back up to temperature and could be tested again. The slab dimensions were 404mm x 280mm x 40mm. Impact points were kept separate and at least 100mm from the edge of the slab.

Figure 8.9 shows the results from impact testing 10/40 IAA at the three different temperatures. As one would expect for a bituminous material, the peak decelerations increase when the temperature is decreased because the bitumen is stiffer at lower temperatures. The effect of temperature is further illustrated by measuring the drop heights required for each temperature to give a peak g of 150, 200, 250 and 300g. This is illustrated in Figure 8.10.

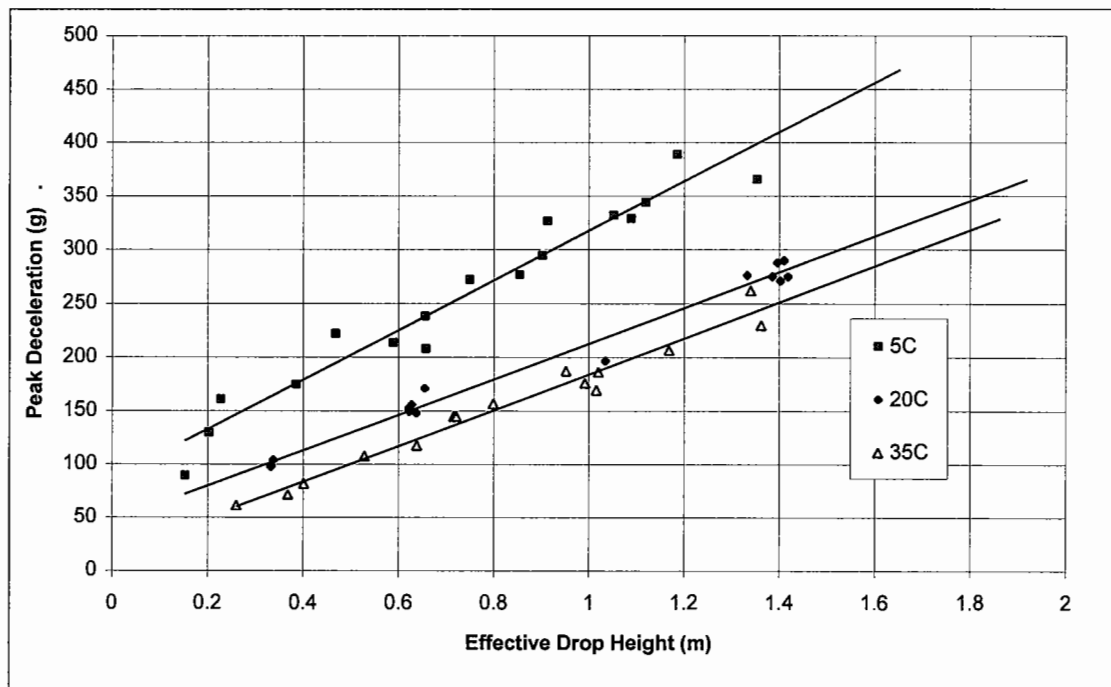


Figure 8.9 - Peak deceleration against effective drop height for slabs of IAA 10/40 tested on a concrete base at different temperatures

Figure 8.9 shows that the test temperature does affect the impact severity of IAA 10/40. It also suggests that the lower temperatures have a more pronounced effect on the impact severity. Using this information a relationship of how the test temperature affects the impact severity can be developed to allow results taken in different temperatures to be normalised. This will be carried out in the next chapter in developing a design guide for the impact performance of the material.

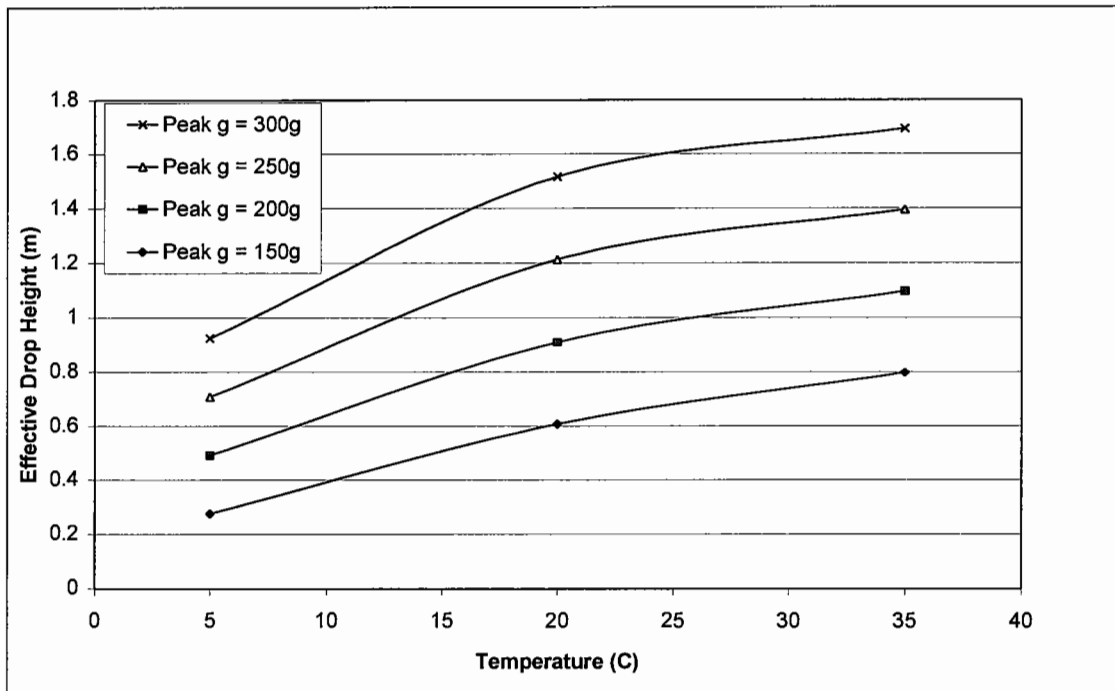


Figure 8.10 - Effective drop height against temperature to demonstrate the changes in peak g for different temperatures of IAA 10/40

Effect of rubber content

The effect of changing the rubber content has been investigated for IAA 10/40. Slabs with varying rubber content between 0 and 35% were produced and then tested on a concrete slab in the impact attenuation test. Figure 8.11 shows the results on the different slabs. It shows that as the rubber content is increased, the severity of impact is reduced. The relationship between rubber content and impact severity is shown in Figure 8.12 through the drop height to achieve a peak deceleration of 200g. It indicates a fairly uniform rise in drop height as the rubber content is increased, but it appears to flatten as the rubber content is increased suggesting that a curve will form an asymptote when the mass of rubber is around 50%.

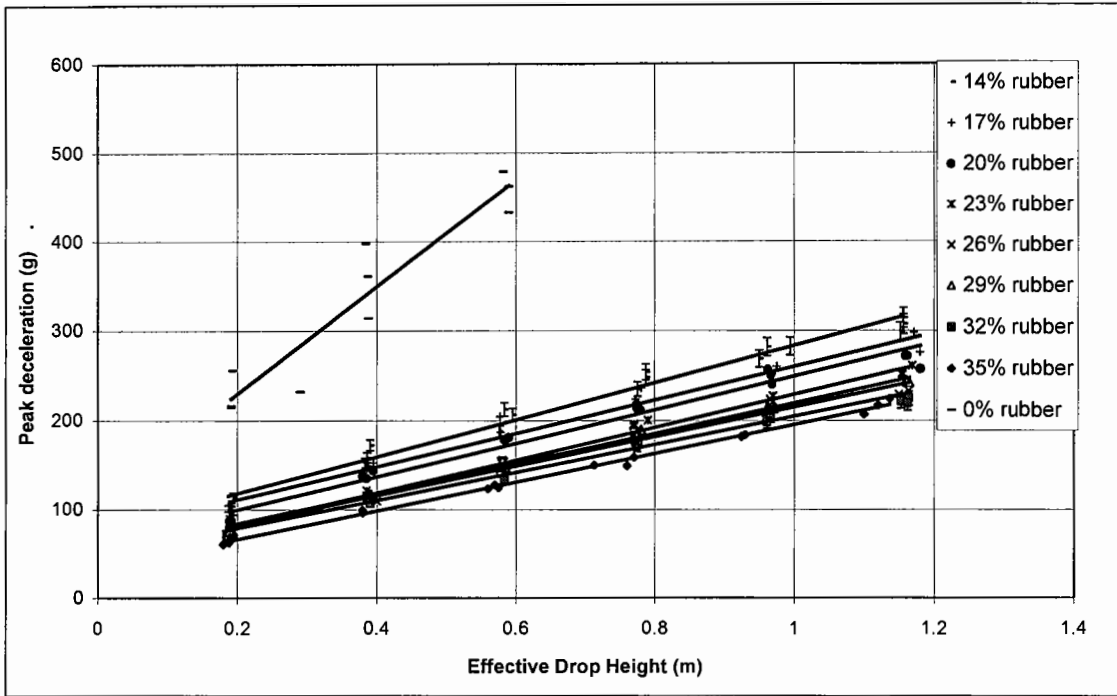


Figure 8.11 - Peak deceleration against effective drop height for slabs of IAA 10/40 with different rubber contents on a concrete base

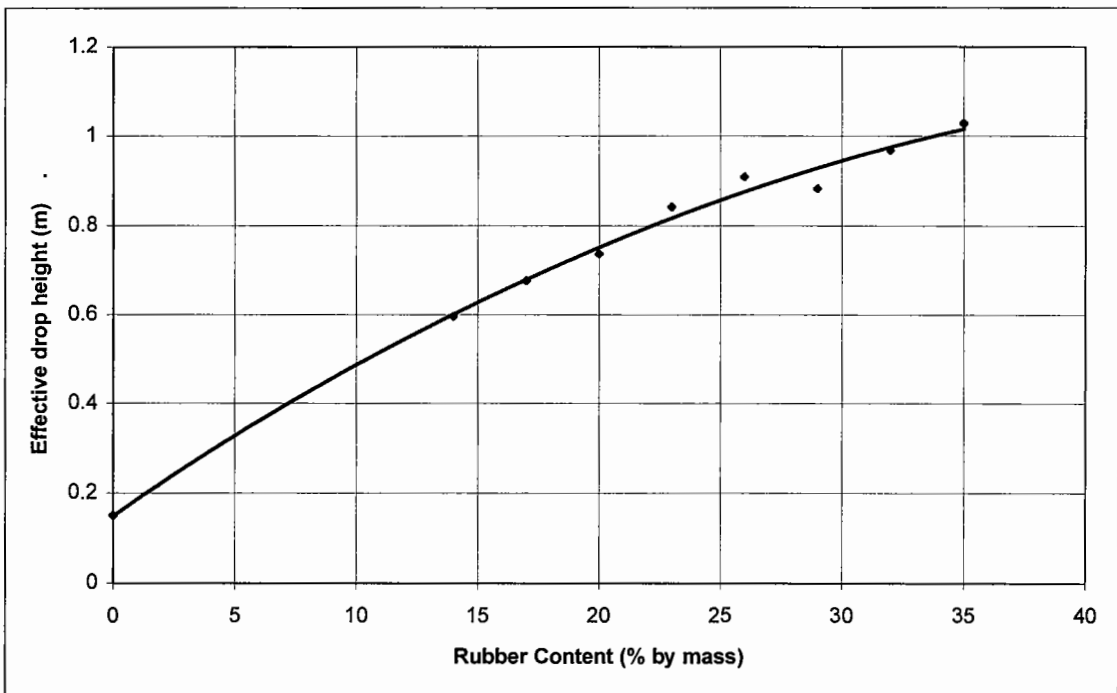


Figure 8.12 - Rubber content of IAA 10/40 against the effective drop height that gives a peak g of 200g on a concrete base

In comparison to the 3/20 mixture, the rubber content in the 10/40 mixture affects the impact severity to a greater degree. This could be because the matrix of the 10/40 material is a looser structure than the 3/20 and the rubber particles are not constrained to the same degree. The rubber particles in the 10/40 mixture constitute a main

proportion of the coarser particles and therefore are large elastomeric inclusions with the aggregate performing mainly as a filler. The 3/20 mixture in comparison is composed of rubber particles that make up a larger proportion of small particles, so the elastomeric inclusions are finer and the aggregate makes up a larger proportion of the coarser particles. The fact that the impact severity for the 10/40 is more sensitive to the rubber content than for the 3/20 suggests that the coarse particles in the material matrix are the main influence on the impact severity. A reason for this could be because when the rubber makes up the finer particles, the coarser aggregate constrains it, whereas when it makes up the coarser particles, the finer aggregate particles do not restrain the rubber and it can function as an elastomeric material.

Changing sub base

The next stage is to develop a series of tests to quantify the effect on impact severity on the sub base material. The aim is to quantify the effect of the effective stiffness of the sub base on the impact severity. A suite of tests using the impact attenuation test on IAA 10/40 laid over sub bases with different effective stiffness values were carried out. Four different sub bases were developed from concrete through to a thin layer of type 1 sub base laid over sand and a thin layer of rubber.

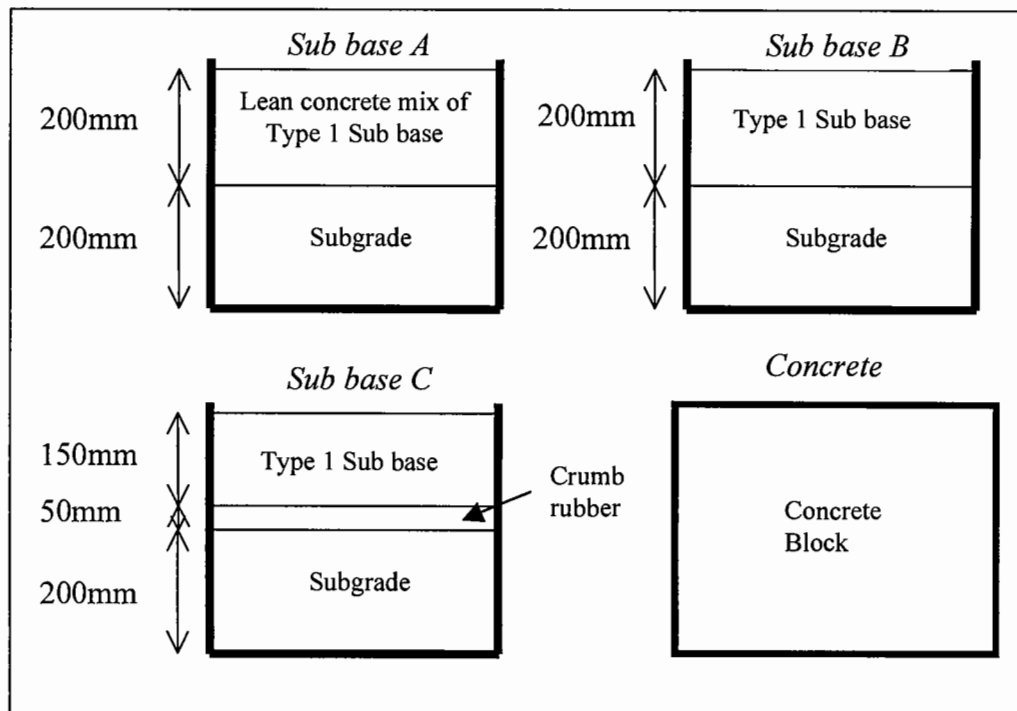


Figure 8.13 - Schematic of the sub base boxes constructed to simulate different ground conditions

A Clegg Hammer was used to give the 'Impact Value' so that the effective stiffness of the sub bases in the boxes could be calculated. The Clegg Hammer is a simple device widely used in evaluating sub surface pavement conditions by measuring the peak deceleration of a flat headed hammer dropped from 450mm onto the surface. The higher the peak deceleration, or 'Impact Value' the higher the stiffness of the sub base. An effective stiffness (K_{eq}) can be inferred from the Clegg Impact Value (CIV) using the following equation.

$$K_{eq} = \frac{100mg(CIV)^2}{2h} \quad 8.1$$

where;

- m = mass of Clegg Hammer
- h = drop height (450mm)
- g = acceleration due to gravity
- CIV = Clegg Impact Value (/10g)

This equation assumes an elastic, sinusoidal contact to give the effective stiffness in terms of the contact area of the Clegg Hammer.

Table 8.3- Results from Clegg Hammer of impact values on sub base boxes for Impact Attenuation Test

Sub base Type	A	B	C	Wigan Sub base	Concrete
Average Clegg Impact Value (CIV)	117	33	8	26	185
Standard Deviation from 10 points	10.9	6.4	1.1	4.8	-
$K_{eq}(N/m) \times 10^6$	68	5.3	0.3	3.4	170

Table 8.3 presents the results from the Clegg Hammer of the 3 sub base boxes produced, the sub base laid at Deanery High School in Wigan for an astroturf pitch and the concrete base under the impact attenuation test in the laboratory. The sub base at the school in Wigan represents a typical Clegg Hammer value for an average sub

base. The CIV value for a subgrade is normally in the range of 6-8 that can be represented by Sub Base C. Therefore the sub base boxes provide a range of effective stiffnesses around a typical sub base. Also, because the surface of the sub base boxes were all, apart from the concrete base, type 1 granular materials, the texture of the material is also realistic.

Initially, a slab of 10/40 IAA was tested on the 4 different sub bases under normal conditions. The nomenclature 10/40 represents the conventional mix design with 29% rubber by mass and a maximum stone/rubber particle size of 10mm laid in a 40mm thick layer. Therefore, for reference, 10/30 IAA and 10/50 IAA represent the same mixture design but laid in 30mm and 50mm thick layers. The results for the tests on 10/40 IAA on the four different sub bases are presented in Figure 8.14.

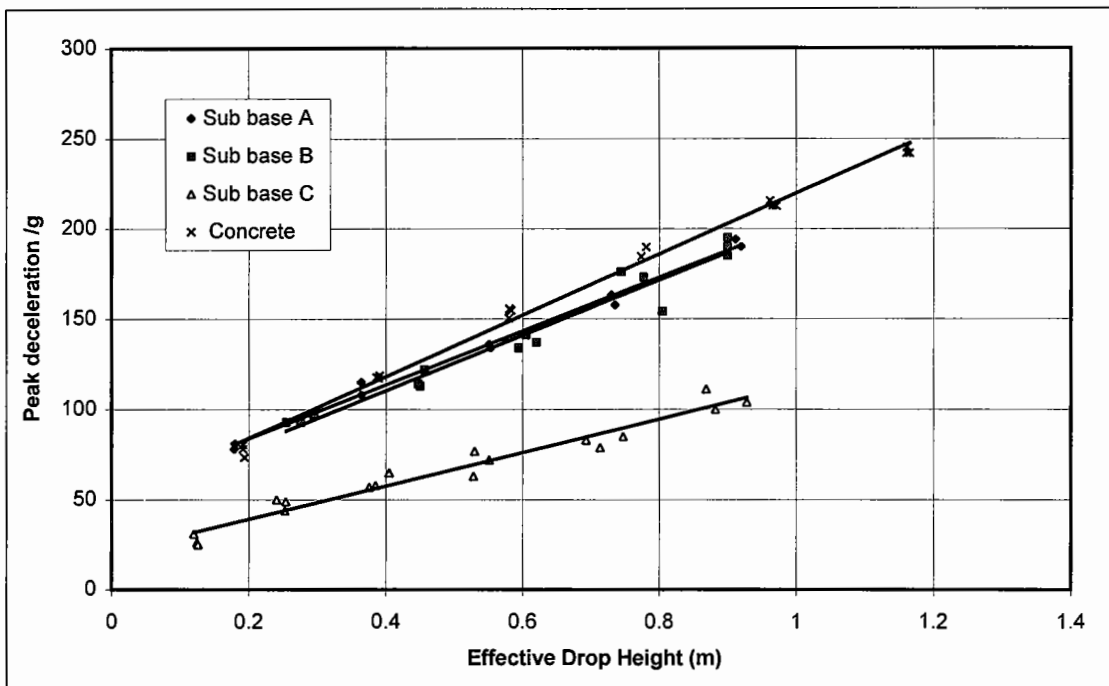


Figure 8.14 - Peak deceleration against effective drop height for IAA 10/40 on different sub bases

The result above shows that the weakest sub base, Sub Base C, has a significant effect on the impact severity when 10/40 is laid over it. However, the systems using the stiffer sub bases A, B and concrete show relatively little difference in impact severity. This suggests that when the sub base has reached a certain level of stiffness, the impact severity of 10/40 when laid over is not effected further.

Changing Material Thickness

The effect of the thickness of the material when laid was investigated by testing slabs of 10/30, 10/40 and 10/50 IAA laid over the different sub bases. Initially, Sub Base A was used with the three different slabs and the results are presented in Figure 8.15. These show that as the slab thickness is increased the impact severity is reduced. This indicates that the thicker the slab, the more influence it has on the impact severity and the more it absorbs the impact.

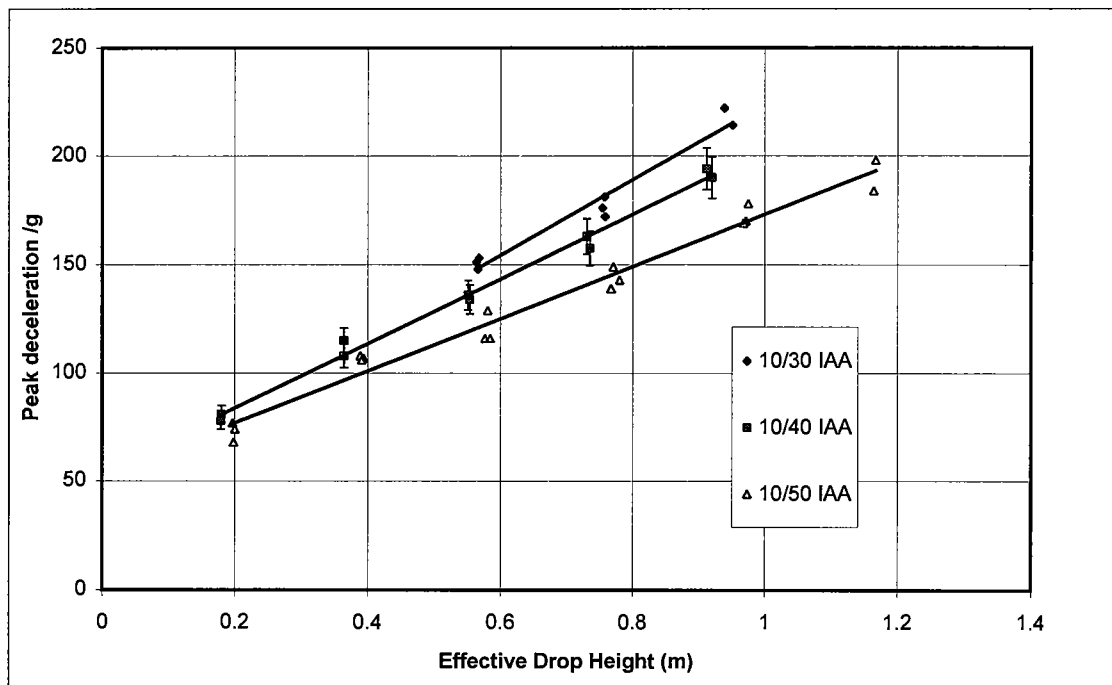


Figure 8.15 - Peak deceleration against effective drop height for different thicknesses of IAA 10/40 on Sub Base A

The error bars on Figure 8.15 represent 95% confidence limits based on a Gaussian (normal) distribution generated from a repeatability study from 20 drops from the same height. These indicate that the difference in impact performance measured is sufficient to illustrate a change because of the depth of the slab. The effect of the other sub bases on the different slab thicknesses is summarised in the discussion section.

Effect of surface layer

It has been indicated that the 10/40 IAA material is intended for use as a sub layer for an artificial sports turf. Therefore, in-service, the material will have a sanded carpet laid over the top to provide a sports surface comparable with grass. The effect of the carpet on the impact performance of the system must be assessed so that results on the material alone carried out in the laboratory or in the field can be factorised to account for the effect of the carpet. This will enable the previous results taken on the material to be adjusted so that the in-service performance can be estimated.

The carpet used was a sample of artificial turf with 25mm thick pile. 20mm thick layer of sand was used to fill the pile as this is used to provide structural stability for the turf and also to aid in drainage. Figure 8.16 illustrates results taken from a slab of 10/40 IAA laid over Sub Base A with and without a carpet. This indicates that the carpet reduces the impact severity of an impact. The gradient of the lines of best fit suggests that the addition of the carpet reduces the impact severity by a constant factor, regardless of the force of impact.

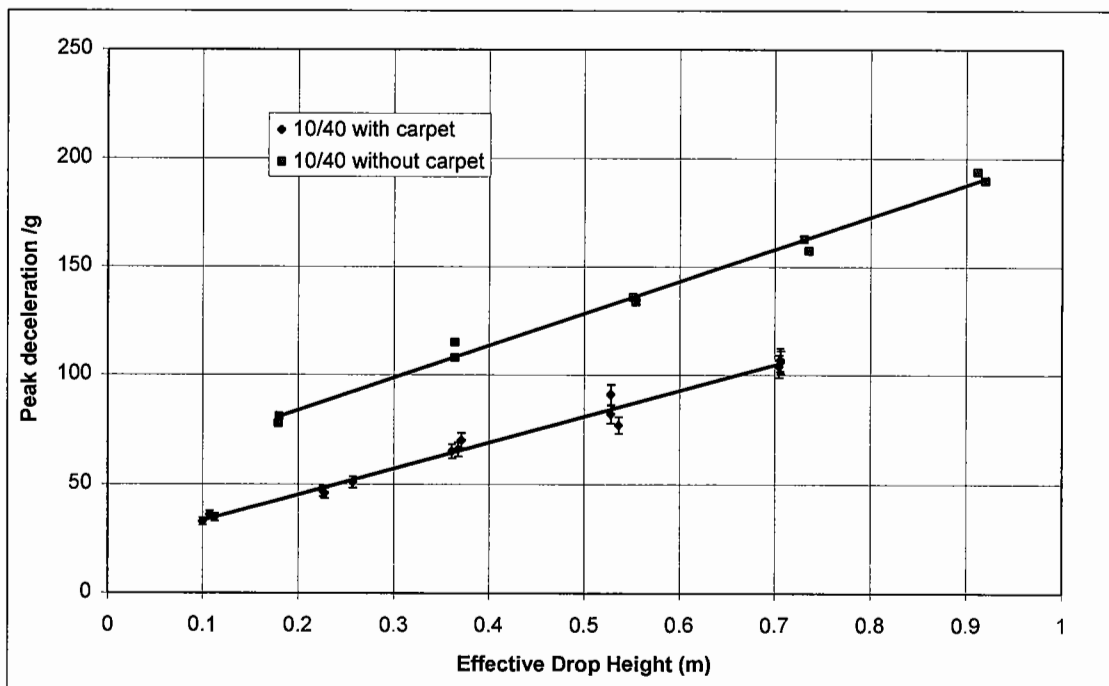


Figure 8.16 - Peak deceleration against effective drop height for 10/40 IAA on Sub Base A with and without a sanded carpet laid on top

In-situ Material

An artificial sports turf pitch was contracted at Deanery High School in Wigan in February 1999. A sub base layer was constructed and then had a layer of 10/40 placed over it by a paving machine. Unfortunately, the laying and compaction of the material led to a failure in tolerance levels, so the material had to be replaced before a carpet was laid over it. However, it provided an opportunity to take measurements of the performance of the material when laid in-situ.

The impact attenuation test was adapted to enable it to be taken on site and measurements were taken on the material, without the carpet. A section of material was then removed and the Clegg Hammer was used to estimate the stiffness of the sub base. These results are presented along with the sub base boxes in Table 8.3. Figure 8.17 shows the impact attenuation test results taken on site at Wigan are compared with the results on a slab of 10/40 IAA laid on Sub Base B, as this represents a close comparison to the field sub base.

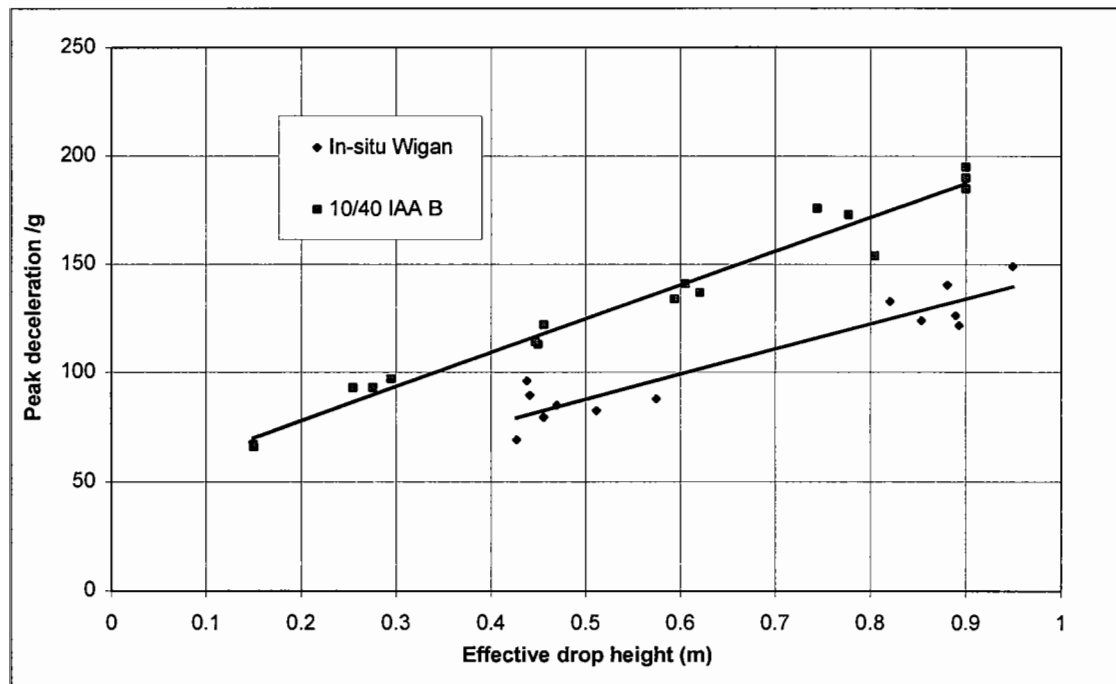


Figure 8.17 - Comparison of peak deceleration against effective drop height for in-situ produced 10/40 IAA with laboratory produced.

The result above indicates that the material laid in-situ and placed on the sub base has a lower impact severity than the material produced and tested in the laboratory. A

closer inspection of the in-situ material showed that it was 60mm deep instead of the intended 40mm. The reason for this was initially thought to be because the material was not compacted as well. Measurements of the density of the in-situ material and the material made in the laboratory showed that the laboratory was slightly better compacted giving a density of 1560kg/m^3 , compared with 1510kg/m^3 for the in-situ compacted material. This shows that the in-situ method of compaction is not as effective as the laboratory method because the material is allowed to rebound when it is still hot. The improvement in impact absorption for the in-situ is probably due to the difference in density and the increase in depth of the material. The actual affect of each parameter on the impact severity will be addressed in the development of the design guide.

8.3.3 Summary

The results taken for the effect of impact performance on the sub base stiffness, the slab depth, the effect of a sand filled carpet and the in-situ measurements can be collated to help produce a design guide that indicates the impact performance of a material depending on the different factors. They have indicated that the sub base stiffness, the thickness of slab and the carpet all have an effect on the impact performance of the system. Further testing has been carried out on the sub bases with different thickness of slabs to develop a chart that is presented in Figure 8.18.

Figure 8.18 indicates a relationship between the sub base stiffness and the impact absorbing properties of the system. It also shows that the thickness of slab is important through all types of foundation. The main indication is that the foundation stiffness is important for the impact absorbing performance of the material if it has a lower Clegg Impact Value (CIV) lower than approximately 40. The result from the in-situ compacted specimen at Wigan tested in the laboratory and in the field has also been placed on the chart. This illustrates a similar shape of curve for the influence of the foundation stiffness. It would appear that the curve for the Wigan sample is shifted vertically probably because of its greater thickness and decrease in density over the laboratory produced specimens. This information can be used to develop a design guide where the material parameters based on thickness, foundation stiffness

and target density can be used to estimate the impact absorbing properties of the material.

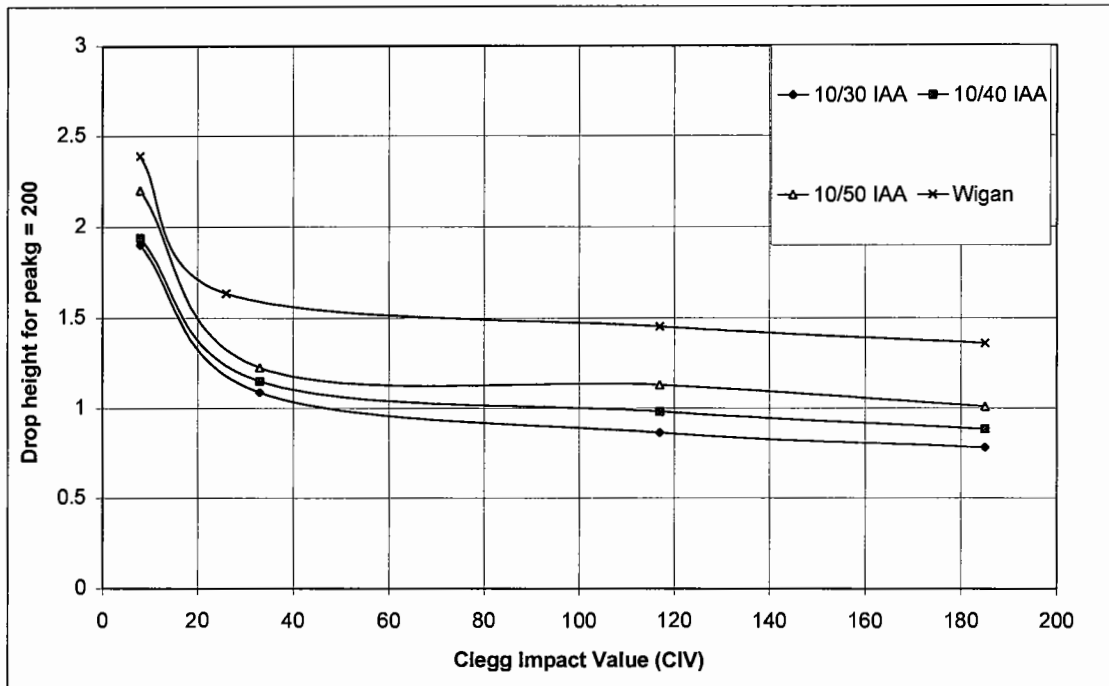


Figure 8.18 - Comparison of effective foundation stiffness through the Clegg Hammer results and impact severity for different types of 10/40 IAA

8.4 Summary and Conclusions

This chapter has focused on the impact attenuation test. The first section described the testing procedures based on the British Standard and developed at the University of Nottingham for safety surfaces on play areas or sports surfaces. The testing carried out on 3/20 IAA was then presented based on a material functioning in play areas. This testing was carried out in conjunction with the testing in the abrasive wear test described in Chapters 5 and 6. Different mixture designs were tested to find the optimum mixture design that provided a material that was impact absorbing and had good mechanical durability.

The effect of the rubber content was assessed by comparing the impact absorbing properties of materials with 0, 2.5, 5, 10 and 15% rubber crumb by mass. The laboratory produced specimens showed that the mixtures containing 5, 10 and 15% rubber differed a small amount compared to the mixtures containing 0 and 2.5%

rubber. A similar comparison was carried out on in-situ compacted specimens. These showed that the results from the laboratory compacted specimens had a higher impact severity than the in-situ compacted specimens. This is because the densities of the laboratory specimens were greater due to the different method of compaction. Essentially, the material when compacted, has a tendency to rebound because the rubber is compressed. The laboratory compaction method does not allow this rebound by leaving a dead weight on the material until it has cooled and the bitumen has stiffened sufficiently to restrain the rubber. This method was chosen because it results in slabs with a good re-productibility. The in-situ compaction method has no method of leaving a dead weight on the surface, so it allows some rebound when the bitumen is hot and fluid and therefore unable to restrain the rubber from rebounding. Therefore, the laboratory specimens have higher densities, which increase the impact severity of the material.

The effect of bitumen content in the mixture on the impact absorbing properties was also investigated and no comparable difference could be ascertained. Mixtures with 10, 12.5 and 15% bitumen content were made and when tested in the impact attenuation test all gave similar results.

The effect of short term ageing on the impact absorption was also measured by testing specimens that had been aged in the oven for 1, 6 and 24 hours before compaction. The impact results indicated that the 6 hour aged specimen gave a higher impact severity than the 1 hour aged, but as the material was furthered aged the impact severity was reduced. Two areas were identified that had an effect on the impact performance of the material. The major one was linked with the density of the specimen tested. The greater the density the higher the impact severity because more of the rubber is restrained reducing its effectiveness as an absorbing medium. The density of the specimens that were short term aged was effected by the interaction between the rubber and the bitumen. The bitumen is becoming stiffer as it is aged with the rubber. Therefore, it is initially less workable and more difficult to compact quickly, illustrated by the decrease in stiffness for the short term aged in-situ compacted specimens. However, it is also stiffer and will allow less rebound when cool, shown by the short term aged laboratory compacted specimens. The second, less dominant area that affects the impact performance of the material is the fact that the

rubber softens as it absorbs proportions of the bitumen. The effect of this property on the impact absorbing properties of the material is yet to be ascertained as the density of the specimen appears to be the more dominant factor.

The impact testing carried out on 10/40 IAA has been more detailed because of the larger number of parameters that can affect the impact performance. The aim of the testing was to assess what factors affect the material as part of a layered system for an artificial turf area. The results could then be used to either estimate the impact performance of the material based on the test conditions, the foundation stiffness, the mixture design and the thickness or alternatively design a material that will perform when laid over a foundation and under certain conditions. Overall, the intention was to produce relationships between different parameters and the impact performance on which a design guide could be based.

The effect of test temperature on the impact absorbing properties of the material was first measured by using a standard mixture design and testing on a concrete foundation. The concrete foundation was used to provide a consistent surface. The results indicated that the temperature does affect the impact performance of the material and that a relationship between the temperature and the peak deceleration could be generated as part of a design guide. Essentially, the cooler the specimen is, the higher the peak decelerations are, showing that the impact severity of the specimen is increased. The main cause for the sensitivity is the performance of the bitumen in the mixture as this is the constituent that is the most sensitive to changes in temperature.

The effect of the mixture design was assessed by impact testing specimens with different rubber contents. A large range of specimens were made ranging from 0 to 35% rubber content by mass. The impact results showed a fairly uniform relationship between an increase in rubber content and the impact severity that appears to peak at a rubber content of around 50%.

As already mentioned 10/40 IAA was to be used as part of a layered system where it is laid over a foundation of a typical paving sub base material and then has an artificial turf carpet placed over it. Therefore, the effect of these parameters had to be

assessed to see how influential they were on the impact absorbing performance of the system. Firstly, the foundation stiffness was assessed by impact testing the material laid on sub base boxes with different effective stiffnesses. The effective stiffnesses of the sub base boxes were assessed using a Clegg Hammer, a simple on-site evaluating tool. The results showed that the stiffness of the foundation does have an influence on the impact absorbing properties of the system up to a threshold stiffness. Generally, if the Clegg Impact Value (CIV) is below 40 for a foundation, the foundation does have an affect on the impact absorbing properties of the system. The lower the foundation stiffness the better impact absorbing the system is. If the Clegg Impact Value (CIV) is greater than 40, then the foundation stiffness does not affect the impact absorbing properties to a further degree.

The thickness of the 10/40 IAA was changed to assess the influence of the depth of the layer on the impact absorbing properties of the system. The results showed that as the thickness of the layer is increased, the peak decelerations are decreased. This trend was repeated through all the types of foundations used. Impact testing was carried out on an in-situ trial at Wigan Deanery High School and related to the testing carried out in the laboratory. A sample of 10/40 IAA was also taken from the site and tested under laboratory conditions. The results showed that the in-situ produced material gave better impact absorbing properties than the laboratory specimens. There were two reasons for this increase, firstly, the material was 60mm thick and also had a lower density. The laboratory specimens have a higher density because the material is compacted and a dead load is applied. The in-situ material has no dead load and therefore the densities are lower.

The impact testing on the material in-situ and removing a sample and testing it on the sub base boxes in the laboratory helped confirm the relationship between foundation stiffness and impact severity. Despite, the difference in impact absorbing properties, the shape of the curve of impact severity and effective foundation stiffness was not changed. This gave an indication that the curve could be transposed by corrections for thickness and density to provide an indication of how the material would perform if produced and tested in the laboratory.

A sanded artificial turf carpet was placed over a specimen of 10/40 IAA to enable the influence of the carpet to be assessed. The addition of the carpet increases the impact absorption of the system by a constant factor. This factor can be applied as part of the design guide to estimate how the material will perform as part of the layered system.

The next stage is to develop practical guidelines for both of the materials. Practical guidelines for the 3/20 IAA can be based on the impact performance, the mechanical durability and how long the material is expected to be short term aged. The practical guidelines for the 10/40 IAA can be based on the impact performance, where the effect of the rubber content, test temperature, foundation stiffness, layer thickness and addition of surface carpet can be altered to design a suitable material.

9. PRACTICAL GUIDELINES

9.1 Approach Used

The foregoing chapters of this report have demonstrated that the Impact Attenuation Test is a suitable test for investigating the impact absorbing performance of a sports or playground surface. The abrasive wear test has been developed and practical evidence given to show that the test is a useful tool for predicting the mechanical durability of a playground surface. These two instruments have therefore been used to collect data in developing a design guide for predicting the performance of IAA.

The production of the material is also addressed with recommendations for methods of construction.

The potential applications for IAA are numerous and it has not been possible to cover all of them through this work. The two main fields chosen are as a playground surface and as a shock pad layer in an artificial sports turf system. The most suitable material chosen for a playground surface was IAA 3/20 and the mixture design can be based around two performance criteria; impact absorption and mechanical durability. The IAA 10/40 was used as the shock pad layer and the impact performance criterion has been based on it as part of the whole layered system.

The IAA 3/20 mixture designed has been investigated by changing the proportions of rubber and bitumen in the mixture. The effect of short term ageing has also been assessed and a recommendation for a suitable mixture design is given. The IAA 10/40 mixture design has been investigated through changes in rubber content and test temperature. The change in impact performance has been looked at by changing the material thickness, foundation stiffness and quantifying the effect of a carpet.

Since there are numerous other variables to consider, such as mixture grading, fatigue strength, long term ageing and bitumen type, the following sections can only be viewed as recommendations and for comparative purposes. However, for both materials a predictive performance guide is given based on the variables investigated

through this work. This will enable the user to design the mixture based on the performance criteria.

9.2 Design Considerations for Impact Absorbing Asphalt 3/20

9.2.1 Mixture Design Considerations

A considerable amount of time has been spent on developing a material that can provide sufficient impact absorbing performance and withstand the abrasion through use and short term ageing. It has been shown that for the in-situ compacted and produced material, the increase in rubber content provides an increased impact absorption. However, coupled to this is that the mechanical durability of the material is reduced through the increase in rubber content and through short term ageing of the material. Therefore, a balance must be struck for a material with a rubber content that provides sufficient impact absorption, but is also durable and will not be affected by the length of time the material is held at a high temperature during transportation.

One way to maintain the impact absorbing properties but improve the mechanical durability is to increase the bitumen content. This has been shown to have little effect on the impact absorbing properties of the material, but does improve the mechanical durability. However, what is not yet known is how the rubber-bitumen interaction occurs while the material is in service. Although the bitumen is less mobile, it is possible that it is still able to flow and diffuse into rubber particles. Therefore, it is questionable whether an increase in the bitumen content will improve the mechanical durability of the material over long term ageing. More practical solutions will be discussed in the next chapter.

9.2.2 Construction Considerations

Another consideration is the ability of the material to compact sufficiently using conventional compaction techniques in the field. The greater the proportion of rubber in the mixture, the less easily it will compact because the rubber causes the material to rebound after being loaded by the compactor. If the material is poorly compacted, it will become a lot less durable and will be more susceptible to long term ageing. It has also been shown that as the material is short term aged, its workability decreases, thus

reducing the ability of the material to be compacted. Therefore, careful consideration has to be taken into account of the workability of the material because if the material is poorly compacted and has a low density it has a poor mechanical durability.

Another factor that effects the ease of compaction is the laying temperature. The viscosity of the bitumen increases as the material cools. Therefore, if the temperature of the material is too low when laid, it will be less workable, resulting in a mixture that has a low density and poor mechanical durability. It has been noted through the on-site trials carried out by Tilcon South at Ballidon Quarry, that the material loses heat at a faster rate than conventional bituminous mixtures because of the inclusion of the rubber. The rubber has a higher thermal conductivity than the aggregate and as a consequence will lose heat quicker. This means that the time allowance between laying and compacting is reduced. The recommended minimum temperature the material should be compacted at is 155°C to get good compaction.

9.2.3 Other Considerations

Permeability

Generally, 3/20 IAA is designed to be impermeable. This is to facilitate it as a surface layer placed over an existing wearing course. Therefore, the existing surface drainage system can be utilised, reducing the cost of construction. This will also reduce the susceptibility of the material to long term ageing, that although not addressed in this work needs to be given consideration.

Friction

Friction between the foot and surface has not been addressed in this work.

Bonding

The nature of IAA 3/20 as a flexible surface necessitates a good bond between it and the lower layer. If the material is not well bonded it will move under the action of

loading, especially lateral movement in the form of twisting, stopping and turning. This can result in surface material that is uneven and structurally weaker.

Ageing

Short term ageing has been shown to have a significant affect on the performance of the material. When the mixture is hot, the fluid bitumen interacts with the rubber diffusing into it, reducing the amount of residual binder in the mixture and changing the properties of the residual binder. This reduces the mechanical durability of the material, and the longer the material is held at high temperatures, the more bitumen is absorbed and the poorer the material is bound together. Therefore, short term ageing is an important parameter to consider when designing and constructing IAA 3/20.

The long term ageing of the material has not been covered in this work. However, indications from the work carried out investigating the diffusion of oils into rubber suggest that the rubber will absorb the bitumen at ambient temperatures. The rate of adsorption and the effect on the material is yet to be discovered, but this could be a potential problem in the longevity of the material. The solution is to produce a material that has a low rubber content so that the effect of the interaction between the rubber and the bitumen is kept to a minimum.

Maintenance

If the material is laid and compacted well, there should be relatively little maintenance required. If the material shows poor levels of mechanical durability, through an inadequate mixture design and/or a long short term ageing period, then the material will need to be replaced.

9.3 Mix Design Recommendations for 3/20 IAA

Testing using the impact attenuation test and the abrasive wear test has led to the conclusion that the best performing mixture is one that contains 5% 1-4mm rubber content, 10% SBS modified bitumen content and 75% aggregate by mass. This material has been found to compact well using conventional compaction techniques.

Also, because of the low rubber content, the interaction between the rubber and the bitumen has a reduced effect on the mechanical durability of the material. The workability of the mix for compaction and the mechanical durability is not changed through short term ageing. This could indicate that the material will also perform well through long term ageing, but this parameter needs to be investigated further.

Figure 9.1 illustrates the expected performance of this mixture if laid in a 20mm thick layer over a conventional wearing course.

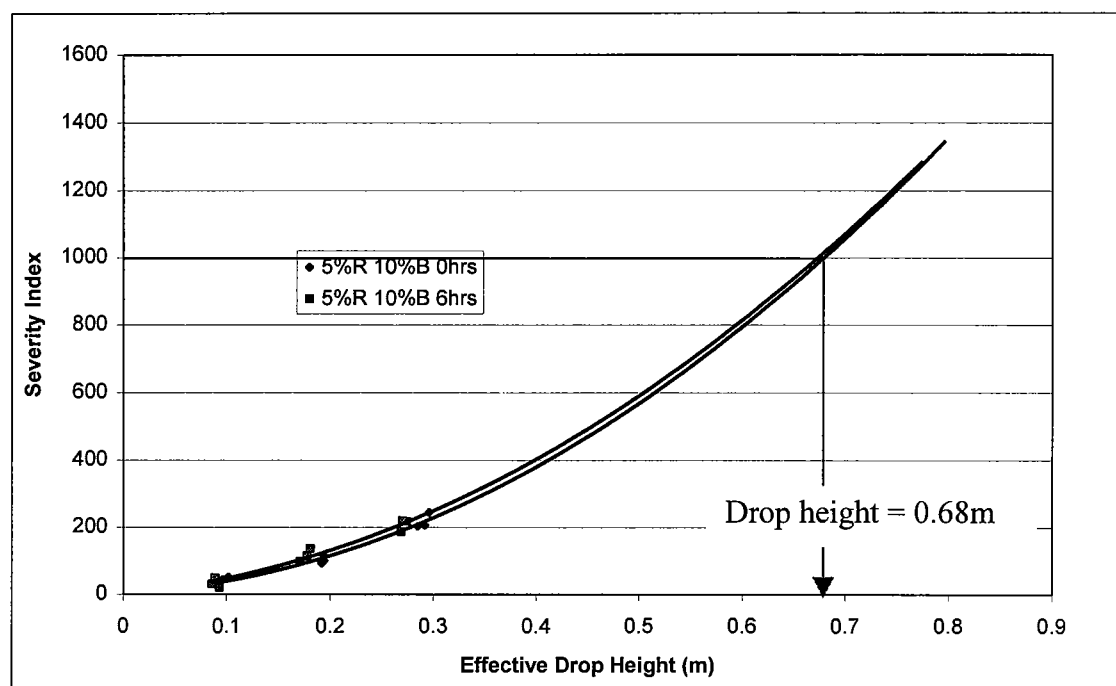


Figure 9.1 - Severity Index against effective drop height for 5% rubber 3/20 IAA compacted in-situ

Figure 9.1 indicates that from a drop height of 0.68m, the Severity Index of the fall will be 1000. Therefore, any drop higher than that on to the surface could result in a fatality according to BS EN 1177 (1998). This is sufficient impact absorption to be classified for a playground surface according to the British Standard.

9.4 Design Considerations for Impact Absorbing Asphalt 10/40

9.4.1 Mixture Design Considerations

The durability of 10/40 IAA is not a major consideration because it is situated below the surface layer. Therefore, it does not have a mechanical surface interaction and is

less prone to problems of mechanical durability. The major performance criteria is that the material provides an impact absorbing layer that along with the other layers provides a surface that performs well for sporting activities. The major parameter in the mixture design that effects the impact absorption is the rubber content. An increase in rubber content decreases the resilience of the material, improving the impact absorbing properties. However, if the material is not resilient enough, i.e. the rubber content is too great, the material will not perform well as a support and sporting activities will be hampered. Therefore, the rubber content must be adjusted to provide a material that provides sufficient impact absorption but does not restrict the activity.

9.4.2 Construction Considerations

The IAA 10/40 layer is designed to be laid over a prepared sub base foundation. It is very important that the sub base is compacted to produce a level area. Problems in early trials occurred because of the flexible nature of the material. When laid from the back of a conventional paving machine, the edge of the material did not stand upright and fell away or 'slumped'. This made it difficult to join the next edge up to it, resulting in a 'V' shaped trough at the seam between two strips. This is not a desirable end product because the tolerances for levels on a playing surface are very strict. Therefore, if the seams do not join together well, the product will fail and have to be replaced. The mix design of the material can be altered to produce a stiffer material at compacting temperature by adding a larger proportion of fine aggregate. This increases the viscosity of the bitumen and thus makes a stiffer mixture. A general guide is to replace 10% by mass of the aggregate dust with a filler to stiffen the mixture sufficiently to avoid slumping. Tests on this improved mixture have been found to have minimal effect on the severity index of the material because the same rubber content is still used.

The material must also be workable enough to enable it to be compacted sufficiently. As the material is not exposed to the surface, the problems of mechanical durability are not encountered. However, the material must still be well bound, to avoid migration of particles. Therefore, compaction is still an important parameter and the

temperature of the mixture must be maintained at above 155°C, to produce a well compacted material.

9.4.3 Other Considerations

Permeability

IAA 10/40 is designed to be permeable. The permeability must be sufficient to remove excess water from the surface quickly, so as not to disturb play, and into the drainage system which is laid beneath the foundations. The material was found to be very permeable through commercial testing although further testing is required to fully quantify it.

Bonding

Bonding is also an important parameter for 10/40 IAA as it is for 3/20 IAA and for the same reasons.

Maintenance

The material once laid, should require virtually no maintenance, as long as it is not exposed to the surface. If the over lying carpet is damaged or removed, the material, as in the 3/20 IAA is likely to fret upon loading. Therefore, care should be taken to avoid exposure to the surface while it is in use.

9.5 IAA 10/40 Mixture Recommendations

The performance testing for IAA 10/40 has enabled the mixture design to be based on a predictive impact performance guide. The idea is to select the rubber content, the test temperature, the depth of the slab, the foundation stiffness based on Clegg Hammer results and if a sanded carpet is to be used. When these have been selected, an estimated drop height to produce a peak g of 200g can be calculated. The equations for this are given below;

For a test temperature greater than or equal to 20°C;

$$D_{200} = 0.55 + \left((0.037 * R) - (0.0004 * R^2) \right) + (0.015 * (d - 40)) + ((T - 20) * 0.013) + ((40 - CIV) * 0.029)$$

Equation 9.1

For a test temperature less than 20°C;

$$D_{200} = 0.55 + \left((0.037 * R) - (0.0004 * R^2) \right) + (0.015 * (d - 40)) + ((20 - T) * 0.027) + ((40 - CIV) * 0.029)$$

Equation 9.2

where;

- D = Drop height to give a peak deceleration of 200g (m)
- R = Rubber content (%)
- d = slab thickness (mm)
- T = Test temperature (°C)
- CIV = Clegg Impact Value for foundation (if >40 then must equal 40)

Using one of these equations will enable the impact performance of the system to be predicted. The equations include the condition of the sub base or foundation and the addition of a sanded carpet so therefore are based the impact performance on the whole layered system. Figure 9.2 gives an example of how the predictive model compares to the measured results taken at Wigan Deanery High School on the in-situ sub base and in the laboratory using the sample collected from the Wigan trial on the sub base boxes. The theory assumes a test temperature of 20°C, a slab depth of 70mm and a rubber content of 29%, which were the measured values on site.

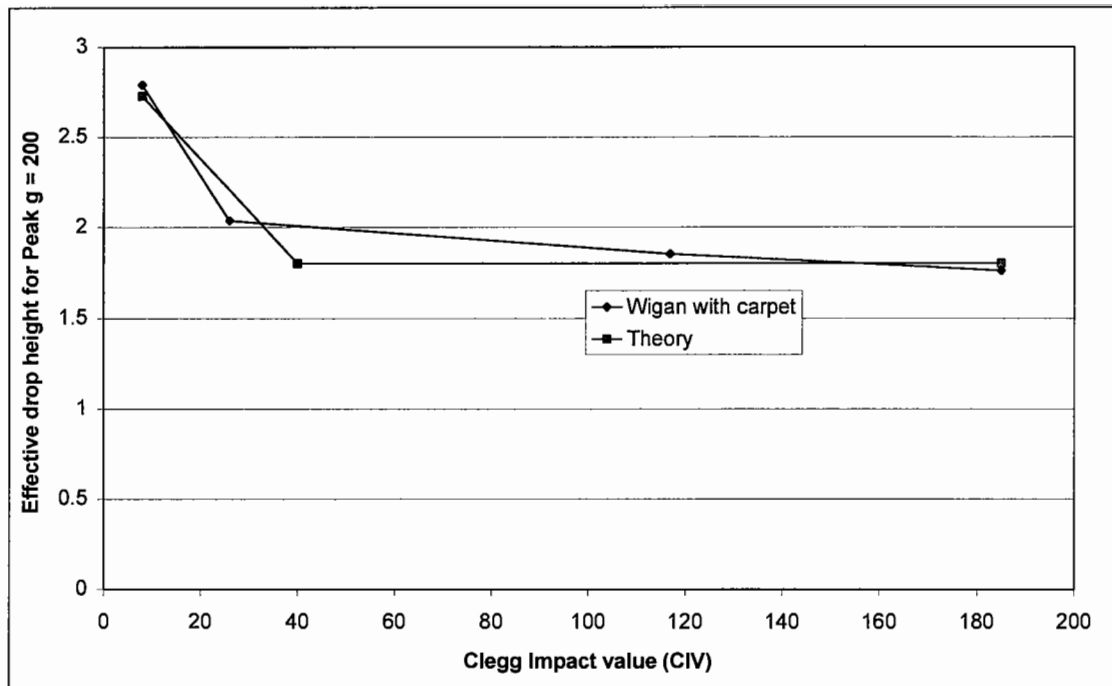


Figure 9.2 - Theory against measured values of Wigan with a carpet

As can be seen from Figure 9.2, the theory provides a close approximation to the actual measured values using the Impact Attenuation test. This demonstrates that a predictive model presented in Equations 9.1 and 9.2 could be used to predict the impact performance of 10/40 IAA as part of an artificial sports pitch if the trial at Wigan is a characteristic of the performance of the material in-situ.

The Sports Council in the UK have established a guideline for measured peak deceleration for the International Hockey Federation to be less than 200g from an effective drop height of 1m and for Football League Standards recommend a peak deceleration of less than 225g from 1.5m. The results from the trial at Wigan illustrate a minimum effective drop height of 1.75m to give a peak deceleration of 200g. Therefore, the mixture design of the material can be adjusted to give a peak deceleration closer to the standard required so that the surface is not too 'soft'. Using equation 9.1 on a foundation with a CIV of 30, slab thickness of 40mm and test temperature of 20°C, the rubber content required to give 200g at 1m is only 5%. This illustrates that the material will perform well with a much lower rubber content than has been used previously. The reduction in rubber content will also reduce problems with compaction because the material will be stiffer and less prone to 'slump' at the edges during construction.

10. CONCLUSIONS AND FUTURE WORK

10.1 Summary

The intention of this project was to investigate the performance of a material that could provide an impact absorbing layer that had the potential to reduce injury, through use or accident, for a sports or safety surface. The method adopted was to replace portions of aggregate particles with recycled crumb rubber in a bituminous mixture containing a SBS PmB binder. The rubber particles make up the larger particles of a continuous graded mixture and act as elastomeric inclusions, making the material 'bouncy'. The aggregate particles provide the material with a degree of resilience, stiffening the material matrix. The intention of using a SBS PmB was that it can withstand deformations because of its high degree of elasticity and will therefore maintain a bound material under impact. However, the principal reason for using an SBS PmB was that it was specified within the patent for which the project was funded. The technology has been shown to provide an impact absorbing layer that can be adjusted in mixture design to suit different impact absorbing criteria. The material produced is termed Impact Absorbing Asphalt (IAA).

The design criteria of sports and safety surfaces require that the material performs in a number of different tests that are defined by different sporting bodies. The most common test is the impact attenuation test, which assesses the ability of the material to absorb impact as a measure of safety. Other design criteria include friction, permeability and durability. Preliminary testing on the original mixture design showed that the material provided adequate performance for all of these except durability. In-situ trials of the material as a surface layer for a safety surface demonstrated that the material frets under mechanical wear, essentially leaving loose particles on the surface. This was judged to be a major problem and for the material to be a good alternative to conventional bituminous materials in playgrounds the problem needed to be investigated and solved.

Preliminary laboratory testing illustrated that the rubber was retaining more of the bitumen than the aggregate. It was discovered, through simulation of the in-situ production of the material, that short-term ageing of the material was reducing the

ability of the material to bind together, effectively reducing the effect of the bitumen as a binder. This led to the conclusion that an interaction between the rubber and the bitumen was taking place, especially at elevated temperatures, which was reducing the mechanical durability of the material.

An investigation was carried out to determine the interaction between the rubber and the bitumen. Initially, a literature study outlined examples of the wet process, where fine crumb rubber particles absorb the bitumen and form a rubber phase within the bitumen. Absorption of oils by rubber showed that it is a diffusion process and illustrated a number of relationships, showing that the particle size, type of rubber, temperature and concentration, all affect the rate and magnitude of diffusion. This aided in understanding the interaction taking place in IAA.

A test method was developed to measure the rate and magnitude of diffusion by curing samples of rubber with the SBS bitumen. The effect of temperature, particle size and concentration were measured to give an indication of the interaction within the IAA mixture. It was shown that the rubber absorbs the bitumen, expands and softens. The mechanical testing of the residual bitumen collected after the curing tests showed that the rheological and cohesive properties are affected through the interaction.

The effect of the interaction on the mechanical durability of the material was then assessed. The Abrasive Wear Test was developed to empirically measure the effect of short term ageing and changing the mixture design on the mechanical durability of the material. The test was developed and shown to give a good repeatability of testing. The effect of short term ageing was found to reduce the mechanical durability of the material. The mixture design was altered to find a method of increasing the mechanical durability of the material.

An impact attenuation test was developed and built at the University of Nottingham and shown to give accurate results of the impact properties of the material. This was used to ensure that changes made to the mixture design to improve the mechanical durability did not adversely affect the impact absorbing properties of the material.

A description of practical guidelines has been produced based on the work undertaken in this research project. It gives details of the main considerations when designing and constructing IAA and also a predictive model for the impact performance of IAA as a layer for an artificial sports turf pitch.

10.2 Conclusions

The main conclusions that can be drawn from the research undertaken in this thesis are:

1. The crumb rubber has been shown to absorb bitumen and swell when added together at mixing temperatures. The rheological and cohesive properties of the residual bitumen, that is not absorbed by the rubber, are altered to a greater degree than bitumen that is cured under the same conditions without rubber. The bitumen composition is also changing and Flame Ionisation Chromatography has shown that the rubber is absorbing the aromatic and saturate fractions more readily than the fractions containing molecules of higher molecular weight (eg. asphaltenes).
2. The Abrasive Wear Test has been developed to specifically measure the ability of the binder to combine the aggregate and rubber matrix in a mechanically durable composite called Impact Absorbing Asphalt (IAA). Through the use of this test it has been shown that the mechanical durability of the IAA, when short term aged, is reduced. This has been shown to be mainly due to the interaction between the rubber and the bitumen that reduces the amount of binder available in the mixture and reduces the cohesive properties of the residual bitumen.
3. An impact attenuation test has been developed at the University of Nottingham to measure the impact absorption properties of IAA. Testing has shown that IAA reduces the forces through impact, thus decreasing the likelihood of injury through falling compared to conventional surfaces e.g. concrete. The resilience to impact is dependent on a number of factors, namely compaction, rubber content, slab thickness, foundation stiffness, temperature, surface conditions and short term ageing.

In addition to these main conclusions, the following lists contain the details drawn from various chapters of the thesis.

Rubber-Bitumen Interaction - Literature Study

The following conclusions have been drawn from Chapter 2:

- The application of adding rubber to bitumen has been widely used in the last 30 years. The two main methods of adding bitumen and rubber are called the Wet Process and the Dry Process. The most successful and popular method to date has been the Wet Process. The Wet Process involves blending the bitumen with fine particles ($<0.7\text{mm}$) of crumb rubber, at high temperatures, prior to mixing with an aggregate. Research in the Wet Process has demonstrated that there is an interaction between the rubber and bitumen that is beneficial to improving the flexibility and high temperature performance of the bitumen. The Dry Process involves addition of larger particles of crumb rubber in the bituminous material mixing process and is the method adopted for production of IAA. To date the interaction between the rubber and the bitumen in the Dry Process has largely been assumed negligible because of the large particle sizes of rubber and the relatively short periods of time held at elevated temperatures.
- Work carried out on polymers has shown that solvents diffuse into polymers causing the polymer network to expand and the particle to swell. The work has led to a number of relationships linking the maximum amount and rate of swelling with particle size, temperature and polymer concentration. The process is likened to the interaction between rubber and bitumen.

Rubber-Bitumen Interaction - Testing

The following conclusions have been drawn from the work carried out in Chapters 3 and 4:

- Rubber is absorbing the bitumen and swelling when held at elevated temperatures.
- The rate and magnitude of swell are increased with temperature and the interaction in the material is at a maximum when the material is at mixing and compaction temperature.

- The lighter fractions of the bitumen are being absorbed, changing the colloidal structure of the bitumen.
- The interaction between the rubber and bitumen alters the rheological and cohesive properties of the residual bitumen.
- For a SBS PmB, within the bitumen dominant region of behaviour (low temperatures and/or high loading frequencies); complex modulus increases, phase angle decreases resulting in a stiffer and more elastic behaviour. This behaviour is consistent with a reduction in lighter fractions, increasing the asphaltene content, making the bitumen less fluid.
- For a SBS PmB, with the polymer dominant region of behaviour (high temperatures and/or low loading frequencies); complex modulus decreases; phase angle increases meaning a softer and more fluid bitumen. This behaviour is consistent with a disturbance up of the polymer sub structure in the bitumen, due to the loss of the lighter volatiles which support the sub structure. Essentially, the bitumen is becoming incompatible with the SBS polymer through the interaction with the rubber. Physical evidence has shown the SBS polymer precipitates out of the bitumen after long curing times with the rubber.
- The interaction between the rubber and the bitumen reduces the cohesiveness of the SBS PmB.
- The investigation into conventional 100 penetration grade bitumens has shown that mainly saturates and aromatics are absorbed by the rubber, leaving a larger proportion of asphaltenes and resins. The fractions are not definitive, but this indicates that the molecules with a lower molecular weight are being absorbed.
- This work has also shown that the composition of the two bitumens did not effect the rate of interaction with the rubber, but did effect the change in mechanical performance due to the interaction. The rheological and cohesive properties of a bitumen with a low colloidal stability index are less effected than a bitumen with a high colloidal stability index (Loeber et al, 1996).

Mechanical Durability

The following conclusions are drawn from the work described in Chapters 5 and 6:

- The rubber-bitumen interaction is occurring in the mixture, particularly at elevated temperatures, reducing the amount of bitumen available to bind the aggregate and rubber and changing the properties of the residual binder as mentioned above.
- The interaction reduces the mechanical durability of the material, which is manifested in the particles becoming loose through abrasion.
- The mechanical durability of the material can be improved by reducing the time the material is held at mixing and compaction temperatures, increasing the bitumen content or reducing the rubber content. The mechanical durability is also improved if the material is compacted well.
- The interaction alters the workability of the mixture by increasing the stiffness of the residual bitumen but decreasing the stiffness of the rubber, thus affecting the density of the material when compacted.

Impact Absorption

The following conclusions are drawn from the research described in Chapters 7 and 8:

- IAA has been found to absorb impact to a sufficient level to reduce the likelihood of injury through an accidental fall.
- The impact severity of an impact on IAA can be reduced by, either increasing the rubber content in the mixture, increasing the temperature of the material or reducing the foundation stiffness.
- Short term ageing reduces the impact severity of the material but also has an affect on the density of the material due to a change in workability of the mixture. Short term ageing increases the viscosity of the mixture at compacting temperatures (155°C), thereby making it less workable during compaction. The achievable density is therefore reduced when using conventional on-site compaction methods resulting in a decrease in the impact severity.

10.3 Recommendations for Future Work

Despite these conclusions a lot is still not known about the material, particularly the interaction between the rubber and the bitumen. If the material is to be a viable product it is important that more work is carried out on improving the mechanical durability of the material as a playground surface as this is the main consequence of the rubber-bitumen interaction. The future work must therefore concentrate on understanding the interaction between the rubber and the bitumen with the intention of developing a solution. The two main areas that can be concentrated on are developing a solution based on the current hot bituminous mixture process and/or to investigate alternative methods of production that will reduce the problem.

The work on IAA produced using a hot bituminous mixture led to the conclusion that the interaction between the rubber and the bitumen is most active at high temperatures. Therefore, the most significant interaction is when the material is held at a high temperature between mixing and compaction. However, it has not been shown whether the interaction is taking place at ambient temperatures and to what extent the material ages after it has been constructed. The long term ageing is therefore an area that needs to be considered when establishing a product that will have good mechanical durability.

The work carried out on the interaction between the rubber and the bitumen has looked at the consequence of the interaction on the mechanical properties of the bitumen. To find a method of reducing the activity of the interaction or the effect of the interaction on the performance of the material it may be necessary to look at the chemistry of the interaction. Thus far it has been assumed that the interaction is a simple diffusion of the lighter molecular weight fractions of the bitumen into the rubber. There has been no real investigation into what happens to the rubber. There is some evidence to suggest that the physical chemistry of the rubber is changing such as the increase in maximum swelling with temperature. Also, although not reported, the SARA analysis on the 100 penetration grade bitumens cured in rubber showed small traces of another material in the bitumen. This may suggest that the vulcanised crumb rubber is reverting, i.e. the cross-links in the polymer structure formed through vulcanisation may be breaking through the consequence of high temperature and the

diffusion of the solvent. However, it is not possible to assume this without chemical analysis on the rubber and bitumen which was not possible through the course of this project due to financial constraints.

It has also been inferred that the bitumen is becoming incompatible with the SBS polymer, causing the alteration of the two phase system in the SBS PmB and possibly precipitating the SBS polymer out of the bitumen. Again, a closer investigation on the chemical reaction occurring needs to be considered.

The intention of investigating the chemistry of the interaction is to develop methods of reducing the affect of the interaction on the mechanical durability of IAA. It has been shown through the work on the penetration grade bitumens that the bitumen composition changes the effect of the interaction, therefore it may be possible to develop an SBS modified bitumen blend or alternative bituminous binders that are not affected to as much of a degree as the present one. It may also be possible to reduce the interaction occurring when the rubber is added to the bitumen, by pre treating the rubber. One method could be to cure the rubber in a solvent, to cause it to absorb and swell, essentially allowing a more reactive solvent to reach equilibrium swelling with the rubber so that when the less reactive bitumen is added it will not imbibe into the rubber.

Another area not fully understood is the rate of interaction of the bitumen in the IAA material. Based on the interaction between the rubber and bitumen cured alone it appears that the interaction is not occurring as quickly in the material because the aggregate in the mixture reduces the ability of the bitumen to diffuse into the rubber. Therefore, a future investigation should concentrate on modelling how the interaction takes place in the material. This will lead to an understanding of the speed of the interaction and help develop guidelines for how much bitumen is needed to accommodate the expected short term ageing of the material during transportation to site.

Another method to combat the problem of the interaction on the mechanical durability is to produce the material using a cold process. This will reduce activity and the magnitude of the interaction between the rubber and the bitumen because the material

will be mixed at lower temperatures and thus eliminate problems with mechanical durability. Bitumen can be applied cold if it is emulsified with water forming bitumen emulsions or diluted with a hydrocarbon solvent to form a cutback bitumen. A cutback bitumen is probably not suitable because the hydrocarbon solvent is still likely to interact with the rubber, however, rubber does not absorb water, so an emulsion is a more viable option. Bitumen emulsions can be added at temperatures up to 80°C and are heterogeneous, two phase systems consisting of two immiscible liquids, bitumen and water, stabilised by a third component, the emulsifier. There are three classes of emulsions:

- cationic emulsions
- anionic emulsions
- nonionic emulsions

The classes refer to the electrostatic charge placed on droplets of bitumen by the emulsifier. A cationic emulsion has a positive charge, an anionic emulsion has a negative charge and a nonionic has no charge on the bitumen droplets. The electrostatic charge on the bitumen droplet attracts it to an aggregate particle of the opposite charge, the bitumen droplet adheres to it and the emulsion is broken (Morgan and Mulder, 1995). The problem using this method is that the electrostatic charge on the rubber may not be the same as that on the aggregate and consequently the bitumen droplets will not be attracted evenly to the aggregate and rubber. Therefore, the bitumen may adhere more to one material than the other. This potential problem may be overcome by using a nonionic emulsion, but future work must be carried out on the potential charges of the aggregate and rubber to investigate whether they will be able to evenly break the emulsion.

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APPENDIX

Contents

A1 - Mixture design sheet for original IAA 3/20

A2 - Mixture design sheet for improved IAA 3/20

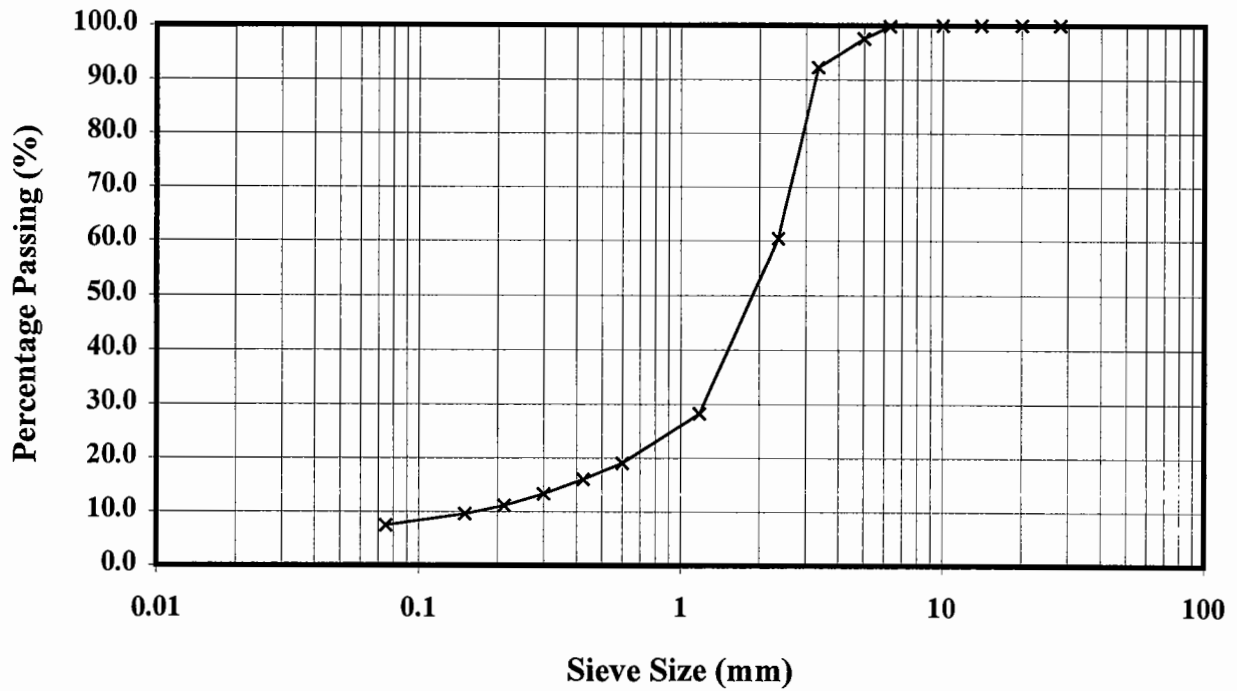
A3 - Mixture design sheet for original IAA 10/40

A4 - Mixture design sheet for improved IAA 10/40

Appendix

Batch Proportions for 3/20 IAA			Original Mixture
Material	15% Rubber		
Slab Depth	20	mm	
Slab Length	404	mm	
Slab Width	280	mm	
Volume	2262400	mm ³	
Design void content	21	%	
6-9mm CL Rubber	0	%	0 g
2-6mm CL Rubber	0	%	0 g
1-4mm Rubber	16.7	%	520 g
10 mm Aggregate	0	%	0 g
6 mm Aggregate	0	%	0 g
Trucal 10	28	%	872 g
Dust	55.3	%	1722 g
Filler	0	%	0 g
Total aggregate	100	%	3114 g
bitumen	10	%	346 g
Total Mass			3460 g

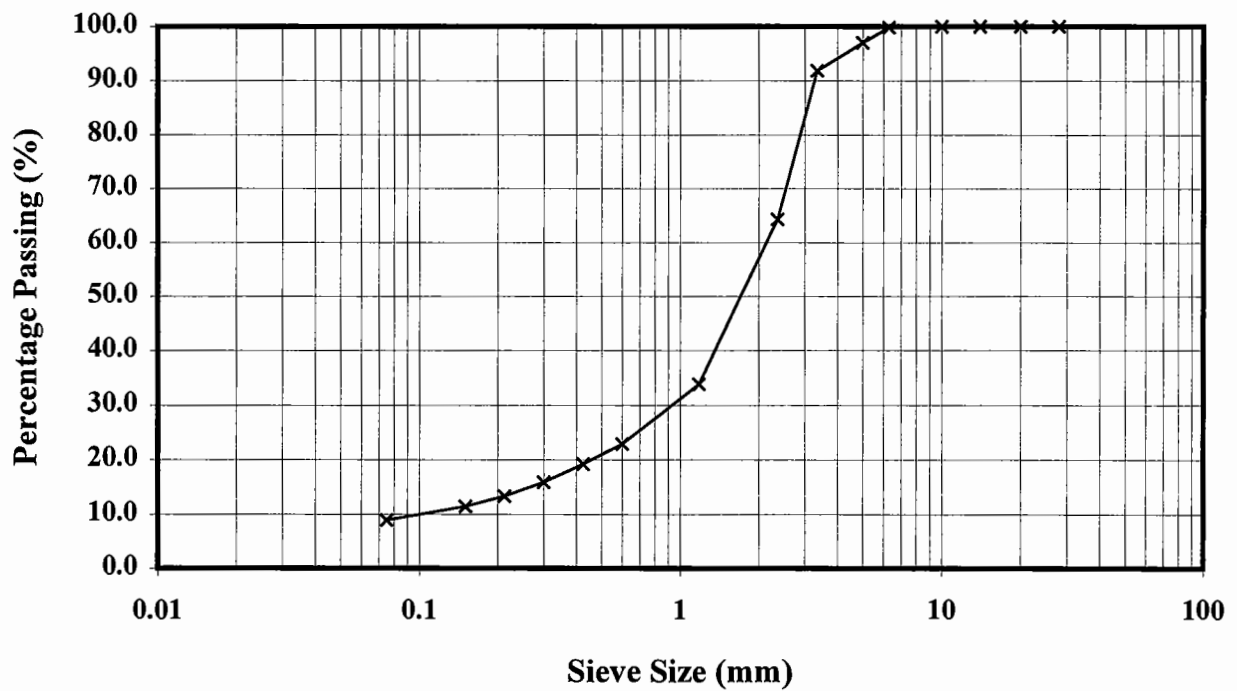
IAA 3/20 Grading Curve



Appendix

Batch Proportions for 3/20 IAA			Improved Mixture
Material	5% Rubber		
Slab Depth	20	mm	
Slab Length	404	mm	
Slab Width	280	mm	
Volume	2262400	mm ³	
Design void content	21	%	
6-9mm CL Rubber	0	%	0 g
2-6mm CL Rubber	0	%	0 g
1-4mm Rubber	5.6	%	194 g
10 mm Aggregate	0	%	0 g
6 mm Aggregate	0	%	0 g
Trucal 10	28	%	972 g
Dust	66.4	%	2306 g
Filler	0	%	0 g
Total aggregate	100	%	3472 g
bitumen	10	%	386 g
Total Mass			3858 g

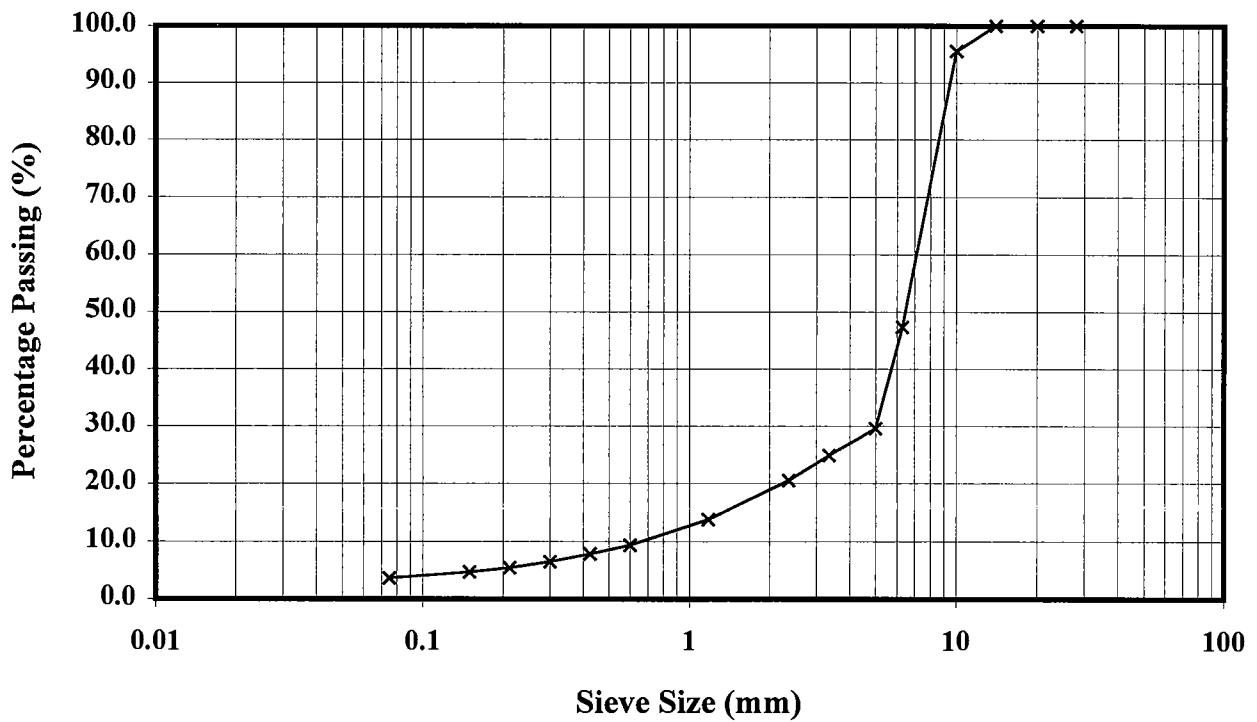
IAA 3/20 Grading Curve



Appendix

Batch Proportions for 10/40 IAA			Original Mixture
Material	29% Rubber		
Slab Depth	40	mm	
Slab Length	404	mm	
Slab Width	280	mm	
Volume	4524800	mm ³	
Design void content	26	%	
6-9mm CL Rubber	32	%	1662 g
2-6mm CL Rubber	0	%	0 g
1-4mm Rubber	0	%	0 g
10 mm Aggregate	34	%	1766 g
6 mm Aggregate	7	%	364 g
Trucal 10	0	%	0 g
Dust	27	%	1402 g
Filler	0	%	0 g
Total aggregate	100	%	5194 g
bitumen	9.1	%	520 g
Total Mass			5714 g

IAA 10/40 Grading Curve



Appendix

Batch Proportions for 10/40 IAA			Improved Mixture
Material	29% Rubber		
Slab Depth	40	mm	
Slab Length	404	mm	
Slab Width	280	mm	
Volume	4524800	mm ³	
Design void content	26	%	
6-9mm CL Rubber	32	%	1663 g
2-6mm CL Rubber	0	%	0 g
1-4mm Rubber	0	%	0 g
10 mm Aggregate	34	%	1767 g
6 mm Aggregate	7	%	364 g
Trucal 10	0	%	0 g
Dust	17	%	884 g
Filler	10	%	520 g
Total aggregate	100	%	5198 g
bitumen	9.1	%	520 g
Total Mass			5719 g

IAA 10/40 Grading Curve

