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TOWARD AN IMPROVED MODEL FOR PERMANENT DEFORMATION OF SBS-MODIFIED ASPHALT MIXTURES

By

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PLAGIARISM STATEMENT

I confirm that this is my own work and does not break the University, school or module conventions on plagiarism as outlined on p10 of the School's MSc in Civil Engineering/Infrastructure/Civil Engineering Mechanics course handbook 2013-2014.

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Signed **Date**

To all those who believe in God, to all those who have faith.

To my wife Nergz and my son Dani

'The future belongs to those who believe in the beauty of their dreams'

(Eleanor Roosevelt)

ABSTRACT

It is a widely held view that permanent deformation, inevitably one of the most serious types of distresses that occurs in roadways. Recent trends in this subject have led to a proliferation of studies that attempt to overcome permanent deteriorations. Previous research has proposed the use of SBS-modifier to improve the performance of mixtures and whether, or to what extent, SBS-modified binders and mixtures lead to achieving a stable pavement. It has been stated that modified mixtures may improve elastic properties that they may improve permanent deformation. The hypothesis that will be tested seeks to explore the effectiveness and usefulness of polymer modified bitumen (PMB) which is considered to be one way of reducing permanent deformation in asphaltic paving materials toward improving mixture performance. This is possibly implemented by attempting to factually investigate and assess the relevance of the behaviour of asphalt mixtures with varying composition to rectify them with a particular consideration of changes to the mixtures.

An experimental programme carried out four tests, in which Multiple Stress Creep Recovery Test (MSCRT) for base binder and PMB followed by three mixture tests – Wheel Tracking Test (WTT), Indirect Tensile Stiffness Modulus (ITSMT) and Repeated Load Axial Test (RLAT) respectively. The mixtures were manufactured for conventional and three SBS-modified binders (3%, 5% and 7% by mass of binder with grade 40/60) with the same aggregate particles.

The main goal of this research project is to shine new light on the emerging role of SBS-modifier in the context of rutting performance as follows:

- *Investigating the fundamental effects of SBS-modified asphalt mixtures for permanent deformation by evaluating the data form binder test through the mixture tests, aiming to provide a comprehensive discussion and satisfactory interpretation supported by reviewed literatures.*

- *Assessing the obtained data from each test in order to determine the optimum SBS percentage likely to be acceptable for permanent deformation resistance.*

The MSCRT data illustrates that the PMBs, particularly 5% and 7% are reasonably influential, which can improve the elasticity of binders associated with non-recoverable (J_{nr}) and percentage recovery (%R) parameters to the extent of being able to improve rutting performance. Furthermore, mixture tests reflect the binder test, at which the *modified mixtures represent better rut resistance, greater stiffness values and less permanent axial strain for each test respectively, specifically at 5% and 7% SBS percentages, which are rather close to each other. Finally, the conclusions provide a brief summary and critique of the significant findings. Since the elasticity response appears to not be the same from binders to the mixtures due to aggregate contribution, it seems that further future research in this field would be of great support.*

Keywords: Permanent deformation, Rutting, polymer, Elasticity, Performance, SBS, HMA, PMB, MSCRT, WTT, ITSMT, RLAT.

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As a rule, I would like to show deepest gratitude to my creator **GOD** for offering me talent, skill, opportunity, perseverance and power to reach this milestone in my career.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Meaning
J_{nr}	compliance of non-recoverable
R:	Percentage of recovery
S_m	Stiffness modulus of asphalt mixture
V_v	Air void content of mixture
ρ_w	Density of water

Abbreviations	Meaning
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American society for testing and materials
BS	British standard
CAR	Compacted Aggregate Resistance
DSR	Dynamic Shear Rheometer
HMA	Hot Mix Asphalt
HRA	Hot Rolled Asphalt
ITSMT	Indirect Tensile Stiffness Modulus Test
LVDT	Linear Variable Displacement Transformers
MSCRT	Multiple Stress Creep Recovery Test
NAT	Nottingham Asphalt Tester
NMAS	Nominal Maximum Aggregate Size
NTEC	Nottingham Transportation Engineering Centre
Pen	Penetration Grade
PG	Performance Grade

PI	Penetration Index
PMB	Polymer Modified Bitumen
RLAT	Repeated Load Axial Test
SBS	Styrene Butadiene Styrene
SBR	Styrene Butadiene Rubber
SEBS	Styrene Ethylene Butadiene Styrene
SHRP	Strategic Highway Research Program
SGC	Superpave Gyratory Compaction
SMA	Stone Mastic Asphalts
SuperPave	Superior performing pavements
VCL	Virgin Crushed Limestone
WMA	Warm Mix Asphalt
WTT	Wheel Tracking Test

CHAPTER ONE: INTRODUCTION

1.0 Background

It is an unfortunate fact that particular sections of roadways are susceptible to different types of deterioration. These have always been in existence since the earliest days of the construction of flexible pavement roads. It is obvious that deterioration leads to increase in discomfort of the roads for road users. This unevenness will tend to repeat the same pattern of deterioration even after each maintenance cycle. This is because of either its inappropriate design or other contributory factors. One of the most striking features of deterioration behaviour is that its maintenance requirement varies enormously from one place to another, depending on the properties of the asphalt pavement components. As the deteriorations are plentiful and tend to continue uninterrupted, in terms of pavement design and specification, the tendency for road authorities has increased nowadays to accommodate the failures that occur on the roadways (Kim 2010).

It will not have escaped the attention of a road user that most of the roads throughout the world are suffering from permanent deformation or rutting as one of the most common type of deterioration in asphalt pavements. Rutting is also one of the major pavement distresses being caused by uncontrolled axle loads, and relatively high ambient temperatures. As described by Donkor (2005), rutting 'manifests itself as a longitudinal bowl-like surface depression in the wheel paths on flexible pavements with the application of vehicular loads'. Thus, the deformed path tends to generate lateral movement on contact with tyre pressure, which may decrease the thickness of asphalt layers with small upheavals to the sides (ibid). Rutting could occur either structurally, which is considered to be the failure of the pavement layers, or it could be non-structural rutting, which is confined within the bituminous layers (Figure 1.1). Fundamentally, the rutting progress is often a combination of the consequence of both mechanisms (Rahman 2004). Conceptually, the central mechanisms of the hot mix asphalt (HMA) rutting could be either due to densification in the early age of the road, when each layer is in contact with the traffic load from the upper layer that spreads and transfers to the layers underneath, which generates rutting due to lack of compaction; or it could be caused by insufficient shear resistance by bituminous mixtures. Thus, if there is shear in one direction, it is a fair bet that there is tensile strain in another. Therefore, the degree of severity depends on the load pattern that tends to cause the deformation (Collop et al. 1995; Donkor 2005; Khan 2008; Miljkovic and Radenberg 2011 and Tarefder et al. 2003).

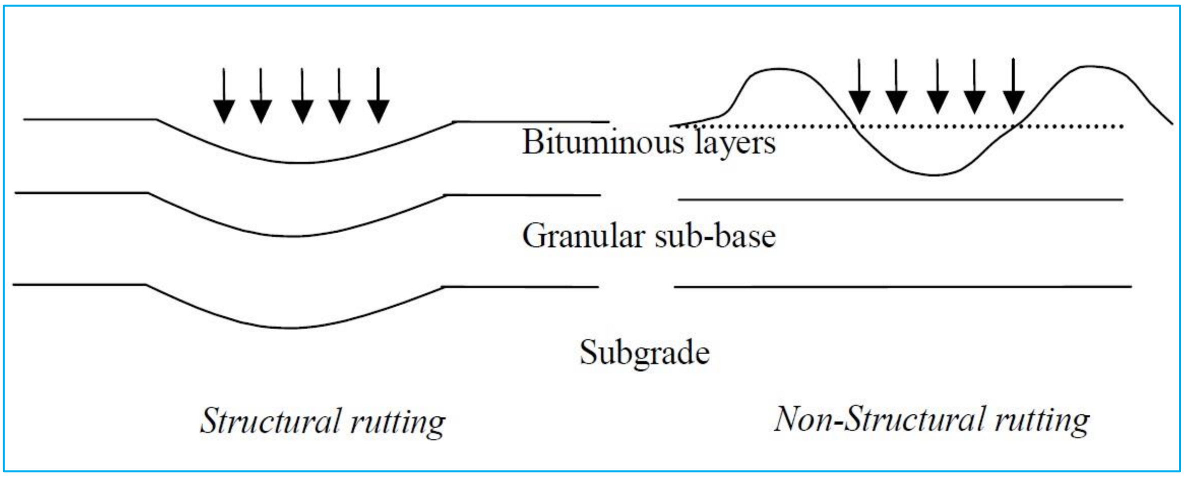


Figure 1.1: Structural and non-structural rutting (Rahman 2004)

Although permanent deformation is inherently problematic and unsafe, it is not an inevitable disaster to control. To design an improved mixture, it is vital to highlight the main contributory reasons of permanent deformation to be taken into account in order to be reasonably corrected. The theory of structural deformations has been investigated and described by many researchers. Many issues with its definition and use, such as the behaviour of the asphalt components, have been considered. In recent years, many types of modifiers have been invented by pavement authorities. Likewise, researchers have evaluated the performance of each of them. One of the key solutions for permanent deformation is a thermoelastic polymer called Styrene Butadiene Styrene (SBS) that has performed remarkably well. Since asphalt is highlighted as a viscoelastic material, SBS could be added to the binder to improve the elasticity of asphalt mixtures after adding to aggregates, particularly in hot environments in which flexible asphalt pavement basically tends to be more viscous rather than elastic (Lavin 2003).

In line with the above view, it has been practically verified by researchers that adding polymer could be an effective factor to improving elasticity of mixtures. Basically, the higher the cost for a section of road, the less maintenance and longer service life that could be attained; meanwhile, a better ride quality is likely to be achieved. Logically, these factors will improve the revenue of the roadways (Soares 2005). This is particularly important in hot climate locations where rutting tends to form. According to Tatic et al. (2006), experimentally, using SBS-modifier in high temperatures offers better rut resistance than in low temperatures. In other words, this confirms that elastic performance tends to work reasonably well, in which permanent deformation is more likely to occur in hot environments due to the tendency of the asphalt towards viscous behaviour.

1.1 Problem Statement and Rationale

Permanent deformation has become the most common type of distress that could impact upon the skeleton of flexible pavement layers, leading to unevenness and discomfort for road users. Firstly, load repetition or axle loads may cause longitudinal deformation alongside wheel movements, which are related to traffic loading. This is of great importance and is taken into account seriously in terms of asphalt pavement design in order to avoid traffic incidents. Secondly, climate circumstances are also an effective factor, especially with rising temperatures; for example, high temperatures may change the rutting characteristics of asphalt materials (Archilla and Madanat 2000 and Tarefder et al. 2003).

Based on the harmfulness of rutting deformation, it deserves researchers' attention and effort to solve. However, it would be difficult, if not impossible, to find a concrete solution in order to resolve this issue. Pavement authorities have spent years of research to define some of the effects, focusing mainly on mixture proportions of asphalt and external factors. These factors, and perhaps others, may lead to huge direct and indirect damages if they are not taken into account properly (Tarefder et al. 2003).

As a crucial advancement in asphalt, SBS polymer plays a vital role with regard to the elastic performance of asphalt. Likewise, different percentages of PMB may change the durability and stability of flexible pavement (Tatic et al. 2006). Simultaneously, the central problem is the real influence of added SBS on the overall performance using correct and suitable percentages by mass of binder, to achieve reasonably appropriate survivability of rutting in typical temperatures. Therefore, diverse laboratory tests that are conducted mainly on permanent deformation may offer a reasonable indication whether and to what extend different SBS percentages could influence permanent deformation performance. This could be defined when there are modified and unmodified mixture samples and perhaps it would be of great insight when the pen bitumen undergoes a binder test separately, before being mixed with aggregates as mixture samples, in order to determine rutting resistance and optimum percentage of SBS.

1.2 Project Scope

1.2.1 Aims of Research

The fundamental aim of this research project is to determine and evaluate an improved model for permanent deformation using SBS-modified asphalt mixtures and to assess the effect of SBS-modifiers with different percentages on rutting performance by finding the optimum percentage of SBS compared with unmodified asphalt mixtures under different laboratory conditions.

1.2.2 Objectives of Research

To ensure the essential aims of this dissertation are satisfactorily targeted, the following objective tasks were set:

i. Firstly, MSCRT (Section 1.5) for the same source of binder and penetration grade, including modified with different percentages and unmodified binder, is undertaken to assess the permanent deformation performance.
ii. To investigate the stiffness of the SBS-modified and unmodified mixtures the samples underwent an ITSMT, which is in correlation with rutting performance.
iii. To evaluate rutting performance, rut depth and axial strain of the SBS-modified and unmodified mixture samples, two asphalt mixture tests underwent WTT and RLAT.
iv. Evaluate whether and to what extent the SBS-modified binders, separately and within the mixture tests, perform using the same percentages (3%, 5% and 7%).
v. Examine and evaluate the permanent deformation performance in the mixture tests and to determine how stiffness relates to rutting and to the presence of the SBS polymer.
vi. Analyze the diversity of the data sets obtained from different test results and compare the various replicated conditions on rutting resistance, consequently determining the optimum percentage of SBS.
vii. Draw well-informed conclusions in light of the critically reviewed literature and the test obtained results.

1.3 Project Limitations

Several limitations affected the course of this research. The most important factors were rather limited time and the desired resources, which are basically related to laboratory capacity to some extent; for example, sample fabrications underwent a relatively longer time than desired. In the experiments, particularly in WTT, there was not sufficient time to provide a longer test duration in terms of the number of passes that could have provided reasonably more data leading to a clearer comparison between SBS percentages (Section 4.3). Owing to lack of resources, there was no opportunity to manufacture the sufficient number of slabs as proposed for WTT.

Most importantly, the slabs had been cored in order to carry out two other mixture tests, ITSMT and RLAT. The trimmed specimens from the slabs might have had been slightly affected due to the deformed path at the reign of the wheel pass near to the core cylinders. Also, 1 cm of the samples were free, which means there was no confinement due to the height of the slabs (60 cm) to be used for other tests (ITSMT and RLAT) after coring and trimming (Figure 1.2). Notwithstanding these limitations, the other tests were controlled within the desired conditions as mentioned in the test parameters.

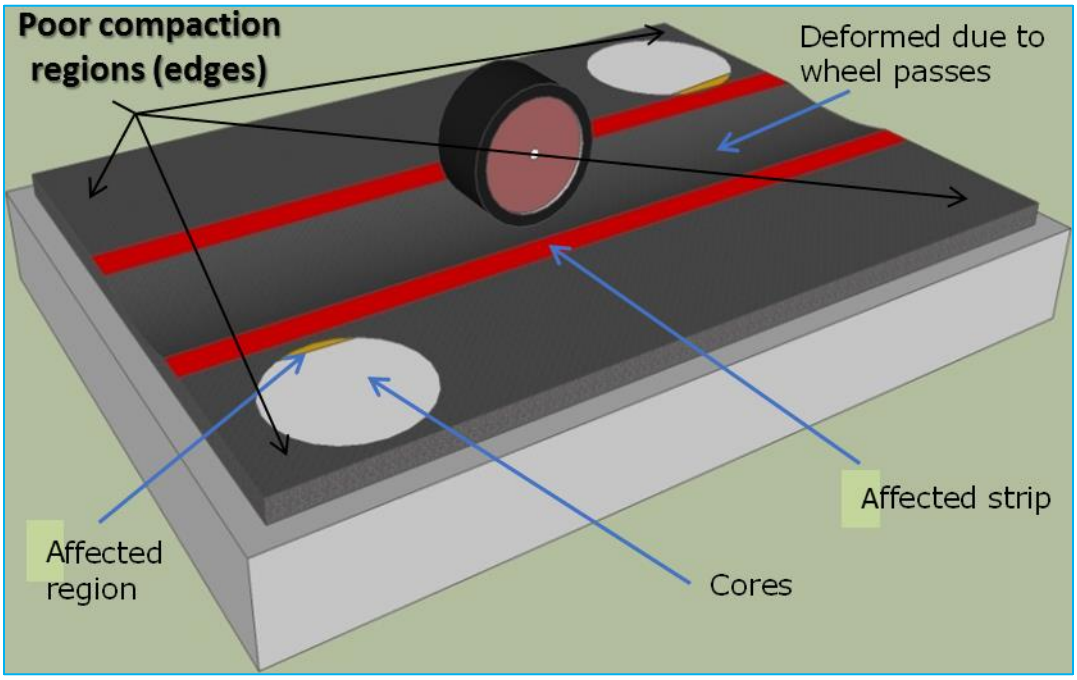


Figure 1.2: Illustration of the main drawbacks of the slab specimens

1.4 Key Questions and Research Hypotheses

In accomplishing the main purpose illustrated above, it is anticipated that the following key questions highlighted by the research project will be satisfied through their acceptance or elimination of the associated hypotheses:

1. To what extent do SBS-modified asphalt mixtures improve permanent deformation performance?

The experimental data reveals that mixtures based on SBS PMB could increase permanent deformation performance, which means this hypothesis seems to be reasonably acceptable. This occurs when the polymer offers better elastic response to the binder compared to unmodified mixtures. Apart from added SBS, careful attention should also be paid to the selection of an optimum binder content with an applicable and appropriate penetration grade, aggregate gradations and skeleton, compaction and air void content.

2. Is it possible to design asphalt mixtures, using optimum percentage of SBS-modified bitumen, which have a sufficient resistance to permanent deformation?

Rutting resistance depends on the percentage of added SBS-modifier. The experimental data will indicate that the SBS-modified asphalt mixtures could increase the permanent deformation resistance to an extent that is represented by the optimum percentage of SBS taken from different percentages.

1.5 Research Methodology

This research project is based on laboratory investigations using modified and unmodified binder and HMA mixtures. Furthermore, the materials proposed for preparation of the specimens were aggregate and bitumen modified with a thermoplastic elastomer polymer, well known as SBS. The mixture components were designed for surface layers and then they were mixed and compacted under standard processes to manufacture the samples. Different SBS percentages (3%, 5% and 7%) were added to the binder in a blending process before mixing with the aggregate according to the specifications associated with each work. The samples of this experiment based research underwent four laboratory tests as a flow approach from binder to mixture tests as follows:

i. **Multiple Stress Creep and Recovery Test (MSCRT)** was undertaken to assess the proposed binder exclusively using modified binders with the above percentages and unmodified binders to determine the permanent deformation performance.

ii. **Wheel Tracking Test (WTT)** was performed to determine rutting depth for the prepared slabs of modified and unmodified mixtures to attain rutting depth.

iii. **Indirect Tensile Stiffness Modulus Test (ITSMT)** was performed to find the stiffness of the mixture for the same aforementioned modification percentages.

iv. **Repeated Load Axial Test (RLAT)** was also carried out on the same cored samples to determine the axial strain of the different SBS-modified and unmodified mixtures.

1.6 Dissertation Structure

This dissertation is composed of six chapters as outlined below:

CHAPTER ONE of this research project brings to light an introduction where a background to the dissertation is laid out. The key problem statements and the rationale are briefly highlighted. Most importantly, the primary aims and the main objectives and the key questions are clearly underlined. Also, research methodology is briefly outlined.

CHAPTER TWO summarizes and reviews a variety of studies and critical analyses of literatures, examining the relevant subjects, synthesizing and comparing different experimental and numerical studies. This chapter also seeks to explore the contributory factors associated with rutting and use of PMB in order to attain an updated picture of the subject from numerous comprehensive studies.

CHAPTER THREE covers the materials used to carry out the tests and the specimen fabrication process, such as manufacture of the slabs and the conditions of selected materials for each replicated condition. The standard specifications associated with the properties of the materials are also presented.

CHAPTER FOUR offers the main methodologies in detail for the laboratory experiments carried out to meet the main objective of this dissertation. Moreover, the importance of each test for this research is also clarified.

CHAPTER FIVE analyzes and critically discusses the obtained results from different tests. The results of each of the four tests are summarized, outlining the main correlation with the conditions and comparison of the collected data. Meanwhile, the interrelations between the tests are also logically indicated, particularly between the binder test versus the mixture tests and the mixture tests themselves, to be more realistically and accurately presented as a logical flow.

CHAPTER SIX summarizes the key conclusions from chapters two to five, and presents the final reflections on this experiment based research project. Finally, a combination of conclusions of the reviewed literatures and the obtained experimental results will close this dissertation with a reflection on where this approach could lead, in terms of further future research that may be carried out on this particular subject as an ongoing problem.

CHAPTER TWO: LITERATURE REVIEW

1.0 INTRODUCTION

The service life of flexible pavement roadways, or more precisely hot mix asphalt (HMA), is generally considered to be designed for at least two decades. However, this consideration sometimes cannot be achieved. This is probably because of several factors, for instance structural (pavement layers) and non-structural factors (behaviour of materials), as evidenced by experimental and field results from reviewing literatures related to characteristics of pavement components and mixture proportions (Soares 2005).

Nowadays, flexible pavement distresses have been considerably increased due to traffic developments, numerous uncontrolled axle loads, new tyre styles with high pressures and changes in temperatures. From this perspective, particular attention has been focused on minimizing the roadway deterioration by researchers assessing essential reasons surrounding this issue. Furthermore, to limit the effects of contributory factors, polymer modified asphalt is proposed, which has received increased attention by the pavement community in passing decades (Airey 2004).

Permanent deformation in asphalt pavements has proven to be an on-going problem throughout a pavement’s service life. Therefore, understanding the mechanisms of the rutting process is a critical step toward better design to attain sufficient durability. While the fundamentals of generating permanent deformations are fairly well known, predicting quantitatively the rate of its progression as a main function is not straightforward and is open to questions and interpretations (Archilla 2006).

A review of past research in this area is necessary to attain a better understanding of possible pavement engineering guidelines. Therefore, the principal aim of this literature review is to investigate the essential factors that lead to the preparation of a standard and favourable model of modified asphalt mixtures preventing non-recoverable deformation. To meet the objectives of this research, a variety of studies have been reviewed with regard to rutting and modified mixtures, by introducing essential reasons behind rutting to gain an updated picture of the fundamental properties of the main components of HMA with and without using polymer modifiers. Likewise, it is highlighted in this literature review that modified asphalt mixtures may improve pavement characterization against permanent deformation.

2.1 Flexible Pavement Distresses

It seems that classifying the main categories of distresses differs among scholars. A number of the most common pavement distresses have been classified by Lavin (2003):

- Potholes
- Fatigue cracking: transverse, longitudinal, reflective, block and alligator
- Surface defects: raveling, flushing and polishing
- Surface deformation: rutting

2.1.1 Potholes

Pothole distress is one of the most serious problems generated for road users and is due to cracks developing from traffic loading and external factors. These can lead to greater holes of less than 1m diameter, starting from smaller ones. Furthermore, the depth of potholes does not remain stable; as well as its size, which increases; sharp and vertical edges can appear from the upper parameters with existing water in seasonal cycles. The contributing factors for potholes are plentiful, depending on the asphalt pavement layers and properties of materials such as aggregate and bitumen (Lavin 2003). According to their shapes, potholes can be classified as three types:

- Low severity: less than 25mm in depth and less than 450 mm in diameter.
- Medium severity: 25-50mm in depth and more than 450 mm in diameter.
- High severity: more than 50mm in depth and more than 450 mm in diameter.

2.1.2 Fatigue Cracking

Cracks in asphalt pavements are considered as a main type of distress, which are generated as diverse shapes according to the influential factors. This issue has become a reasonably prevalent subject for researchers, so that all scenarios during mixing processes are inspected and correspondingly, adverse consequences due to most types of fatigue cracking can be prevented. A recent study carried out by Moghaddam et al. (2011) states that fatigue cracks may appear due to decreasing service life, and the most common example is the alligator type (Figure 2.2), which is associated with repeating wheel loads. As a result, tensile and shear stresses affect the structure of pavement layers which may lead to cracks (Figure 2.1).

In reviewing several studies from the past decade, generally there is no overall agreement among scholars when classifying distresses and understanding fatigue crack. For instance, Lavin (2003) counts other types of fatigue crack such as transverse, longitudinal, reflective, block and alligator despite them having different contributing factors. Fatigue crack is exemplified analytically by Thom (2008), who shows a remarkable breakthrough in describing the initiation of fatigue crack in terms which are easily understood; compared to other engineers, whose ideas contain considerable ambiguity or lack of definition. He adds that it would not be a good idea to consider fatigue in AC pavements as a uniform material like metal, because asphalt is hydraulically a multi-phase component.

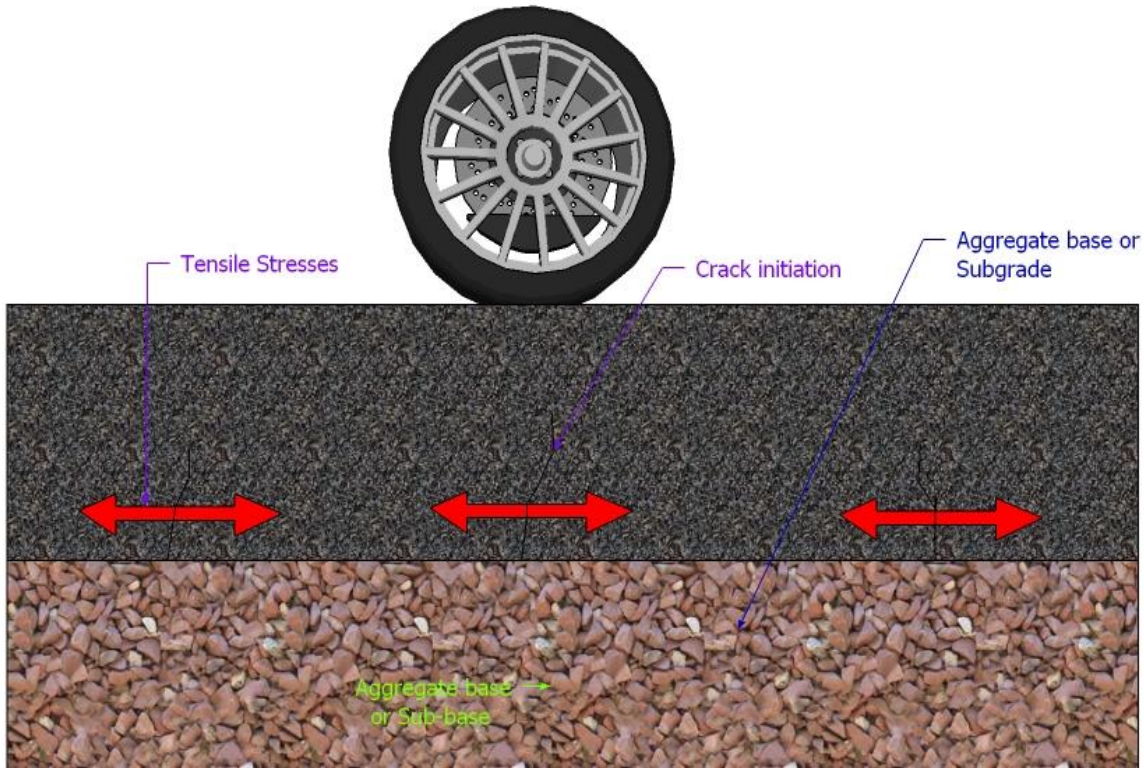


Figure 2.1: Fatigue (alligator) cracking initiation (Lavin 2003)

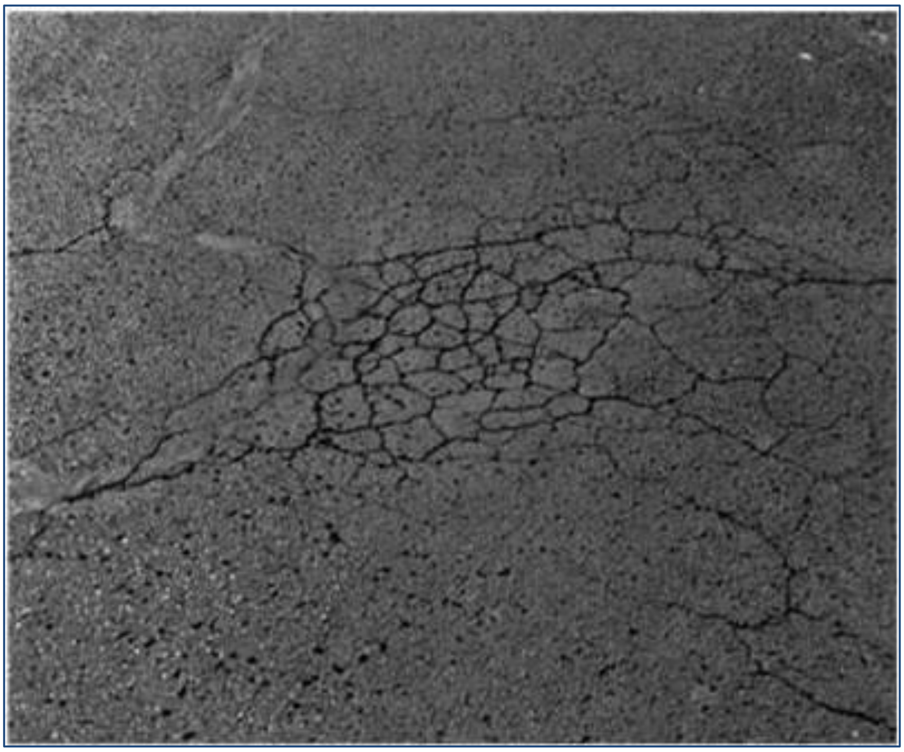


Figure 2.2: Alligator cracking (Moghaddam et al. 2011)

2.1.3 Surface Defects

The contributing factors affecting asphalt pavement surface layer generate some defects which are of great concern to traffic loading. These defects according to Lavin (2003) can be divided into raveling, flushing and polishing; most of them appear due to gradual removal of the surface layer of the asphalt pavement, because of losing bitumen and aggregate. This is probably because changes in temperatures cause brittleness in asphalt, leading to stones separating from the bitumen (Figure 2.3).

(a) (b)

Figure 2.3: (a) Raveling caused by striping (b) High severity raveling (Lavin 2003)

2.1.4 Rutting

Rutting is one of the most common pavement distresses, and it is counted as a harmful problem in asphalt pavement roads. There are several reasons affecting the structures of the pavement layers outlined in detail below (section 2.2).

2.2 Rutting in Flexible Pavements

Definition:

In reviewing the past fifteen years of research associated with rutting, numerous studies have been attempted to define rutting. As described by Tarefder et al. (2003:60), 'Rutting is defined as the formation of twin longitudinal depressions along the wheel paths mainly caused by progressive movement of materials due to repeated loading'. In other words, traffic loads due to the different truck sizes transfer to the pavement layers, with the main impact on the upper layers (Figure 2.4).

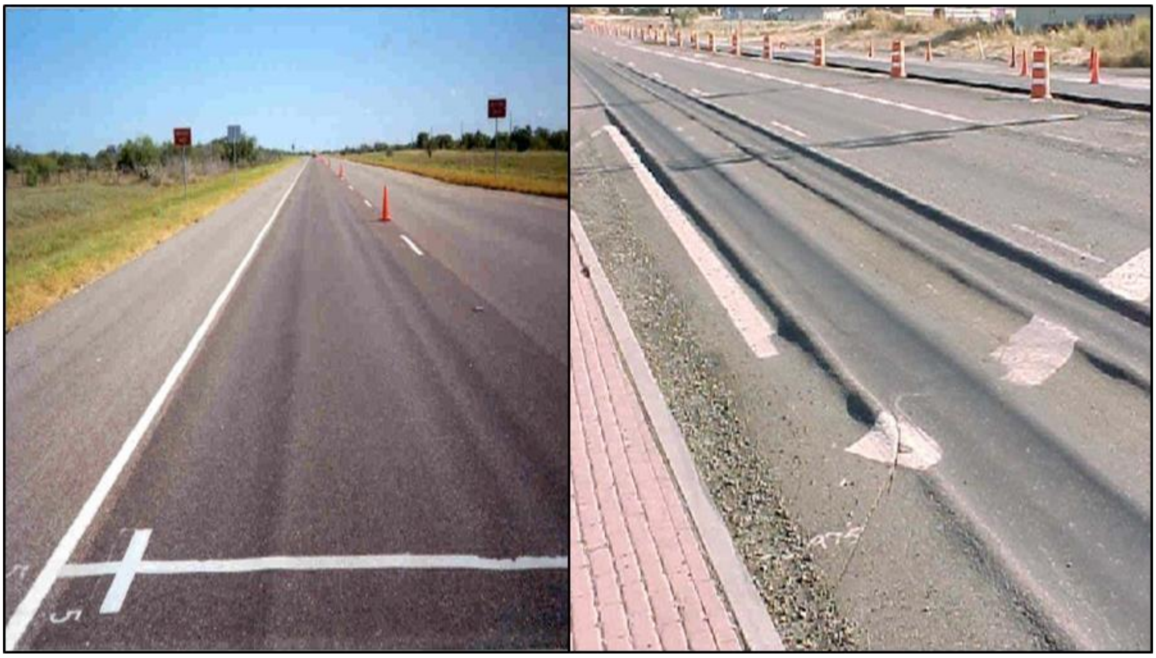


Figure 2.4: Different rutting severities in asphalt pavements (Soares 2005)

2.2.1 Fundamental Mechanisms of Rutting Formation

2.2.1.1 Rutting Caused by Densification (Compaction)

One of the mechanisms of rutting formation is densification which is related strongly to the degree of compaction. Therefore, it has been shown that the degree of compaction to an appropriate density can change rutting depth on pavement layers, which is associated with its viscoelastic behaviour (Collop et al. 1995). In engaging with the densification, Archilla (2006) offers considerable detail regarding the number of factors that can affect rutting behaviour. In this case, the researcher illustrated the use of Superpave Gyratory Compaction (SGC) data for rutting estimation in asphalt pavements. It was found in this model that diverse aggregate density and gradation can change rutting depth obtained by densification slope in the gyratory compactor. The results in this model showed that this assumption was reliable and closely reflected reality as it demonstrated that a strong aggregate structure has sufficient durability to densification in repeated load circumstances. Consequently, the outcome particularly a smaller slope on the densification curve could be noticed, which represents a better mixture. By the same token, increasing the slope reduces the resistance of the aggregate skeleton against deformation.

Moreover, a laboratory-based study on the layers of asphalt by Wang et al. (2009) states that rutting deformation may occur in any layers owing to the dual impact of densification and shear. Figure 2.5 clearly testifies this; depth of rutting appears considerably higher in the intermediate layer along the cross-section. Therefore, particular consideration should be taken into account for all layers in terms of design and material selection.

An earlier study by Khan (2008) reveals that it is crucial to pay sufficient attention to compaction rate and void ratio which are the main causes of rutting. In other words, while traffic movement occurs, applying extra compaction to layers (base, sub-base or subgrade) may lead pavement layers to rut due to densification. On the other hand, lack of compaction is also highlighted in the literature which leads to rutting in longitudinal path wheel trucks along the roads. This commonly generates a 'saucer' shape that could be 750-1000 mm (Figure 2.6a). Therefore, the author selects a typical initial void ratio of 7-8% which may change to 4% under traffic loading. Under these circumstances, Wang et al. (2009) suggest that perhaps it is necessary to utilize some types of modifiers, those which are preferred for rutting resistance in the critical layers such as intermediate, particularly in the heavy truck zones and hot climate areas.

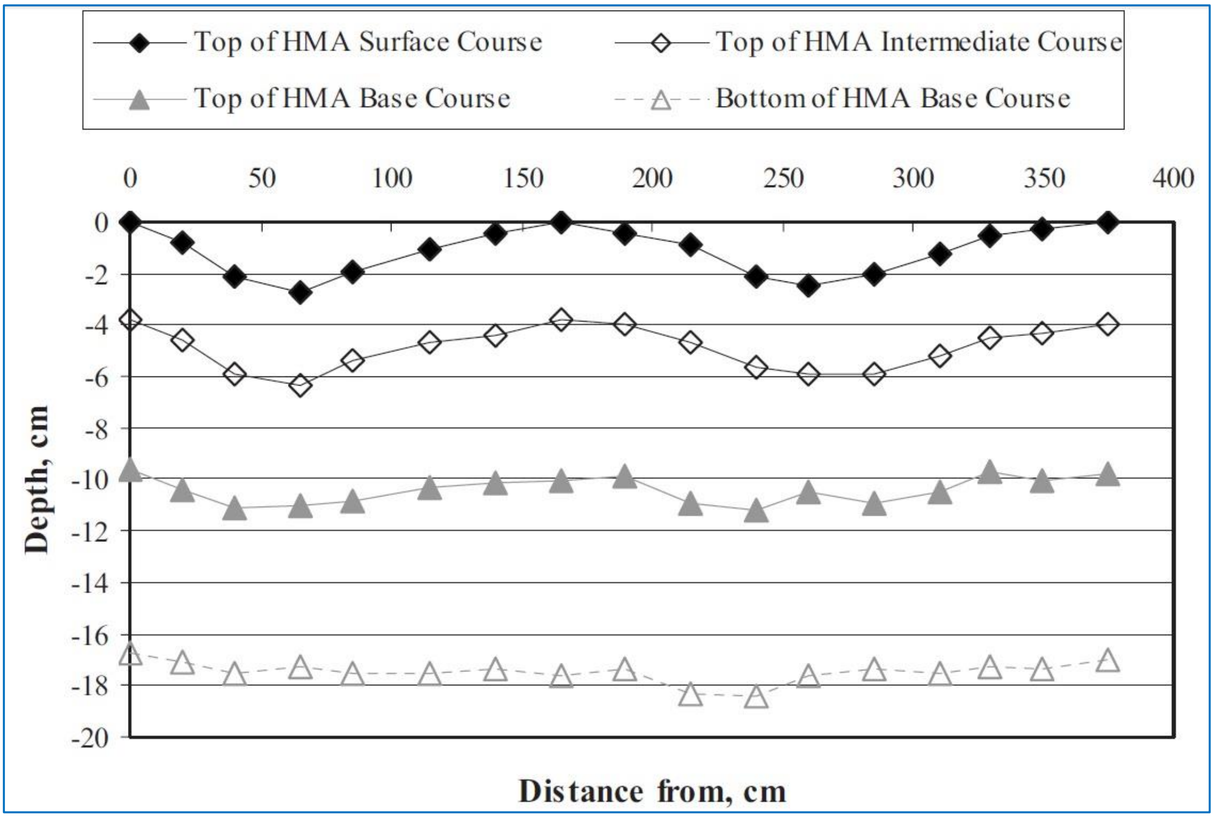


Figure 2.5: Cross-profile of rutting in the pavement layers (Wang et al. 2009)

2.2.1.2 Rutting Caused by Shear Plastic Deformation

Shear failure rutting has been studied intensively by developing constitutive models to predict the behaviour of pavement layers. It was shown that the analytical approaches, using computerized finite element models, are able to make reasonable predictions highlighting initiation of the rutting mechanism by shear failure. It has been demonstrated that initiation of shear failure occurs longitudinally and transversely owing to the pressure of tyre contact (Figure 2.6b). Each of these is in relation to aggregate structures and binder content within the mixtures (Khan 2008). Moreover, the formation of the rutting deterioration (Figure 2.7) can be measured as downward rut depth and total rut depth as a result of wheel paths (Miljkovic and Radenberg 2011).

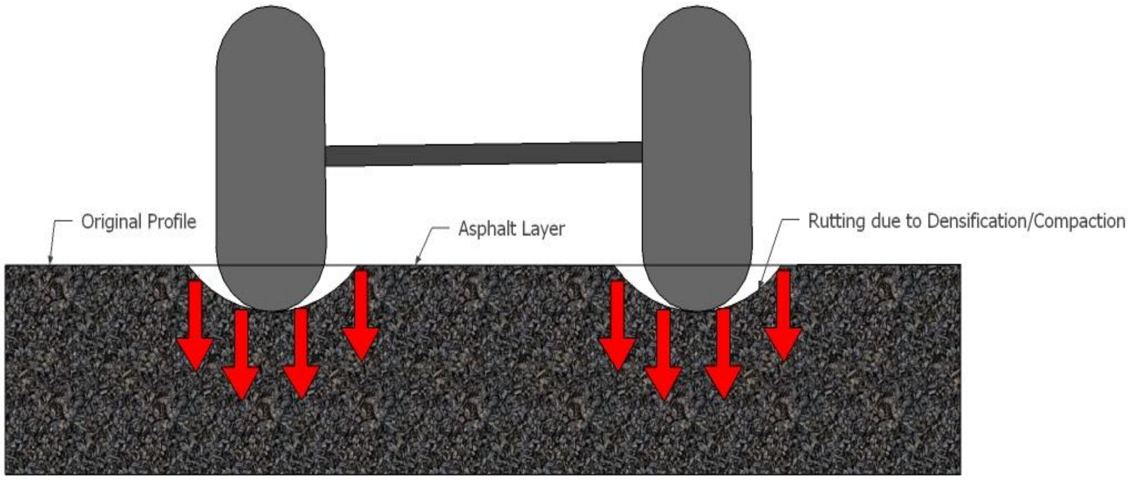
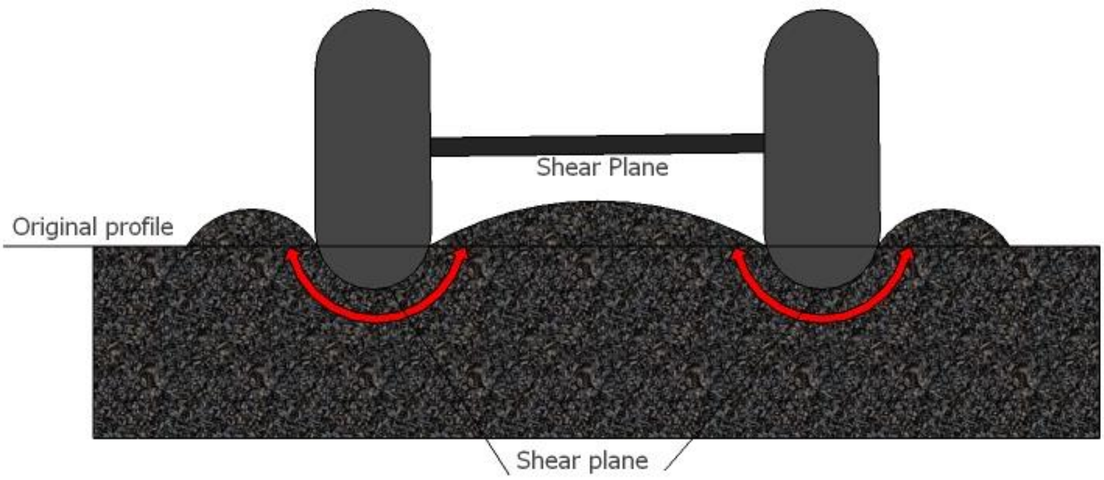


Figure 2.6 a: Rutting due to densification



b: Rutting due to shear failure (Khan 2008)

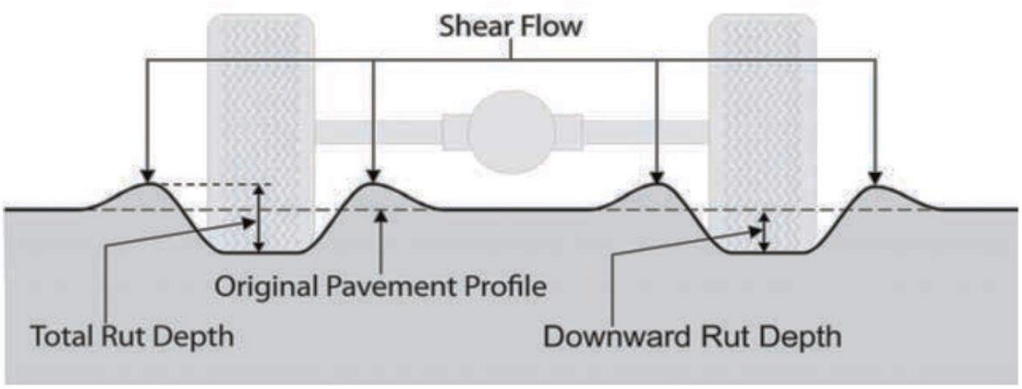


Figure 2.7: Characterization of downward and total rutting (Miljkovic and Radenberg 2011)

In line with the above view, Wang and Al-Qadi (2011) used a 3D finite element model to investigate pavement layer reactions to traffic loading. It was found that the effect of wide-based tyres contacting with the upper layer on the secondary roads generates shear failures, owing to the wide contact area. The size of damage is therefore continuous depending on the contact area with the size of tyre. These loads initiate static and dynamic loads in the contact areas during continuous movement (Figure 2.8). However, the damage ratio could be changed according to the other contributing factors such as layer thickness and temperatures.

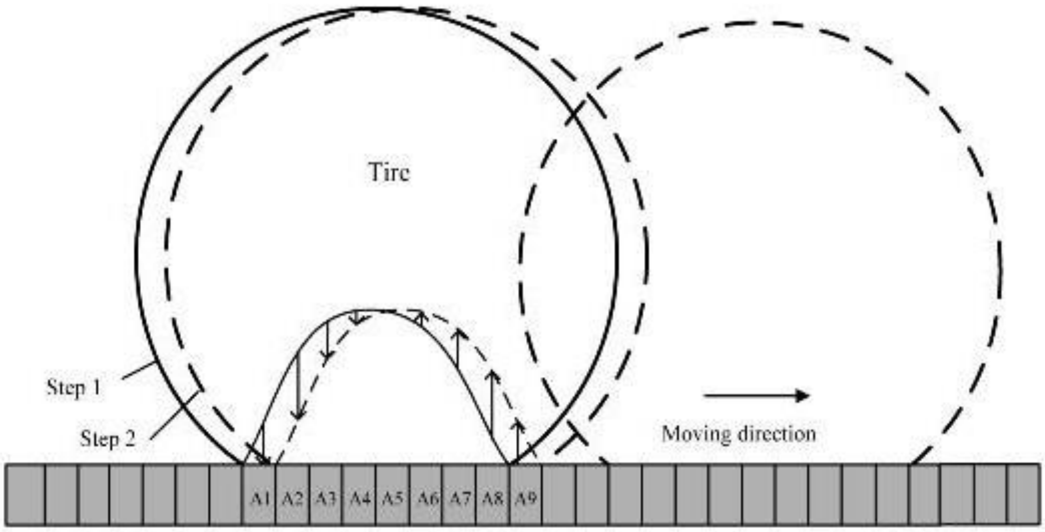


Figure 2.8: Tyre moving along pavement surface (Wang and Al-Qadi 2011)

2.3 The Main Contributory Factors of Rutting

2.3.1 Mixed Proportion Factors

In recent years, behaviour of asphalt mixtures due to their components has been investigated intensively. It has been established experimentally that changing different components of asphalt mixtures such as aggregate shapes, sizes, surface texture and gradation will change rutting performance as shown in Table 2.1 (Miljkovic and Radenberg 2011).

2.3.1.1 Effect of Aggregates

Great interest is shown in aggregate shapes and physical properties, especially unbound granular aggregates and other types (Khan 2008). There are several factors affecting the aggregate characteristics within the asphalt mixtures which may cause permanent deformation. The effects of grain shape and structure (Figure 2.9) are highlighted as an important factor in asphalt behaviour with the influence of sizes and grading relaying to the high bonds. It has been shown that rounded particles have less resistance against slip during load application, while angularity in particles and cubic particles can resist friction forces. In other words, rutting deformation is more likely to happen in gravel-based mixtures rather than crushed gravels (ibid).

With regard to the moisture effects, water levels in lower road locations are able to penetrate into pavement layers. This causes damage within the aggregates that lead to different deformations. The degree of compaction as discussed above represents stability of the layers affected by repeated loads (Uthus 2007).

Laboratory-based research by Topal and Sengoz (2008) undertook a compacted aggregate resistance (CAR) and wheel tracking device test dealing with different aggregates: fine, angular in shape and round types. The results illustrate that using angular particles represent better rutting resistance, and in terms of interlocking the aggregates, worked remarkably well. In contrast, rounded aggregates under construction circumstances conduct better workability than the angular types.

On a larger scale, a similar study carried out by Kim et al. (2009) points out that the impact of aggregate skeleton on rutting performance in low traffic loading is dependent on physical properties. It has been observed that rutting behaviour in Superpave mix gradations can be influenced, particularly in low volume traffic compared with medium and high loading, including crushed aggregates and vice versa, because the system based in the Superpave mixture is generally formulated for cases of medium and high traffic loading. The most interesting point to highlight is that gradation of fine aggregates within the asphalt mixture can provide better rutting resistance, which is not attained from coarse gradations. From that point on, it is crucial to indicate that this procedure simplifies the design and offers advantages, such as greater freedom for using fine aggregate gradation in the case of HMA design. Therefore, this achievement can be targeted as an applicable procedure in terms of factors against rutting in the HMA design method.

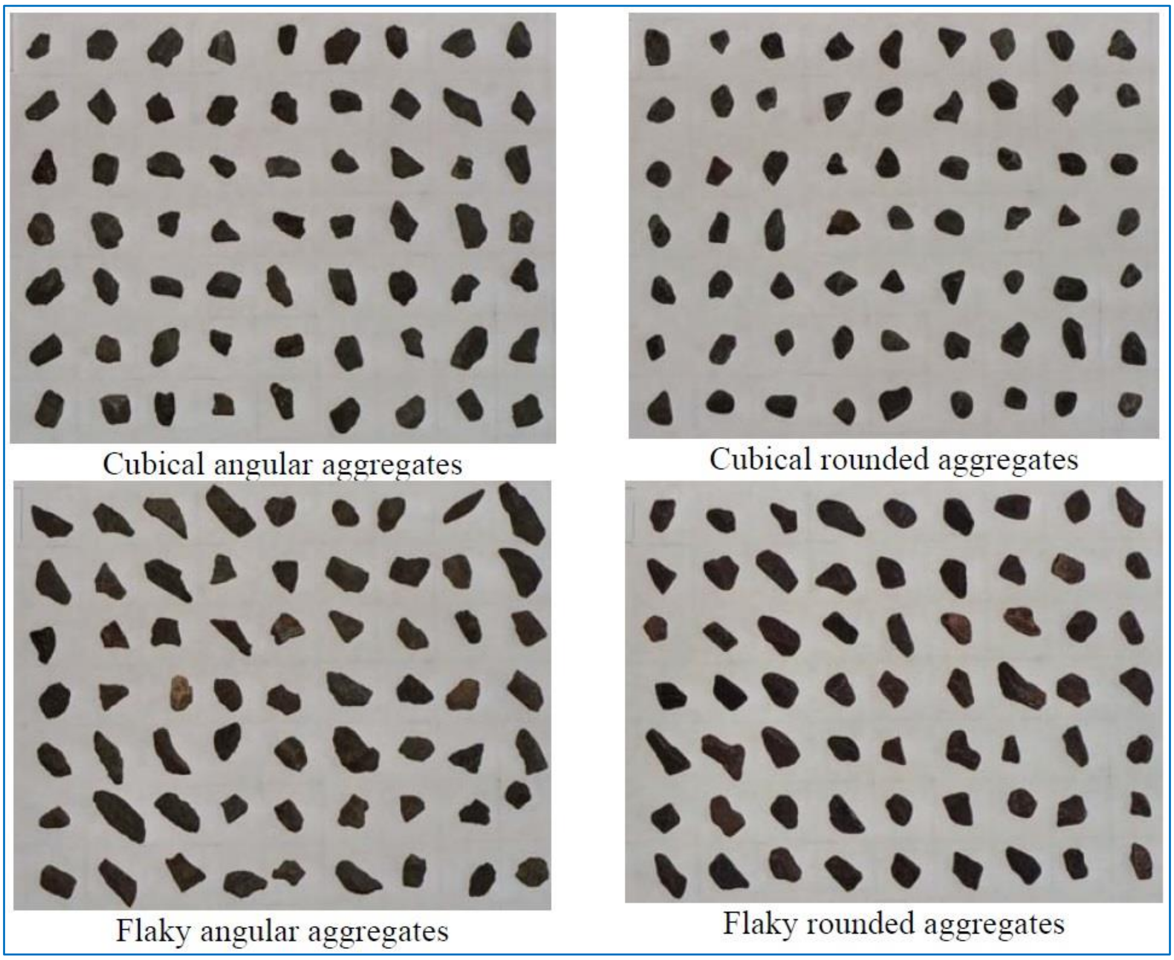


Figure 2.9: Different aggregate shapes (Uthus 2007)

2.3.1.2 Effect of Bitumen

Bitumen, or more specifically, asphalt binder, as the essential part of asphalt mixture has been intensively researched in order to assess its properties. In these cases, the cohesiveness of bitumen and its other physical characteristics with different type of aggregates have been adopted. Furthermore, rutting resistance can be increased with increasing stiffness of bitumen. In contrast, increasing the binder content to more than the optimum rates within the mixtures may decrease rutting resistance (Table 2.1 - Miljkovic and Radenberg 2011). According to Jakarni (2012), adhesion is of great significance, allowing asphalt mixtures to connect with each other (Figure 2.10) providing a strong bond against external loads. Meanwhile, the viscoelastic behaviour of bitumen and binder viscosity is of great importance in cases of different temperatures and loads. The main initiated failure between asphalt binder and aggregates is moisture damage due to weakness of adhesive forces between aggregate particles. This may lead to structural failures and becomes a factor in stiffness loss in asphalt mixtures. As a result, the final consequence would be different distresses such as rutting, fatigue, raveling, stripping. Therefore, it has been proved, based on laboratory experiments, that cohesion and adhesion within asphalt mixtures are crucial in preserving its characteristics against different deformations.

Table 2.1: Mix factors affecting rutting performance (Miljkovic and Radenberg 2011)

Factor		Change in Factor	Effect of Change in Factor on Rutting Resistance
Aggregate	Surface texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size	Increase
Binder	Stiffness	Increase	Increase
Mixture	Binder content	Increase	Decrease
	Air void content	Increase	Decrease
	Voids in mineral aggregate	Increase	Decrease
	Method of compaction		
Test of Field Conditions	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease if mixture is water sensitive

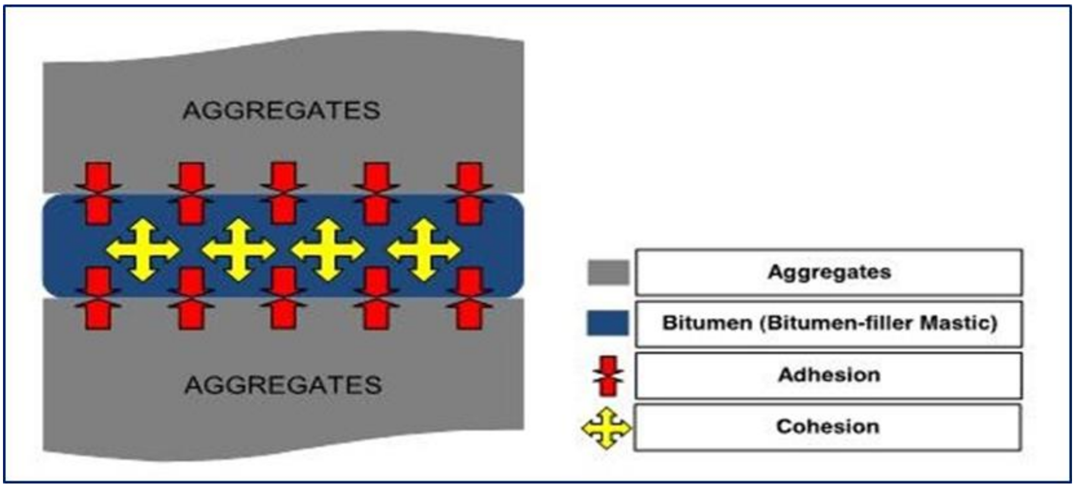


Figure 2.10: Adhesion and cohesion of bitumen-filler mastic and aggregates (Jakarni 2012)

2.3.2 External Factors

2.3.2.1 Traffic Loading

It is undeniable that traffic loading is considered to be one of the essential factors causing roadways to rut. Therefore, there is an extensive body of literature concentrating on traffic loading concerns and their influences on structural deformation (pavement layers) and non-structural rutting (materials) of asphalt pavements, or both. This is perhaps the most intriguing area for ongoing research among pavement engineers and road authorities. In this regard, Thom (2008) addresses different concerns structurally and non-structurally affecting non-recoverable deformation. These factors include type and load magnitude; indeed, a larger traffic volume initiates higher stresses on pavement layers than light loading. Thus, it is difficult to determine differences between variable loads on the asphalt pavement layers precisely. One factor that has been identified in finding asphalt pavement deformation susceptibility is the contact pressure. This effect lies with the tyre contact area, which converts pressure onto the layers that differs with the continuous movement of the vehicle (Figure 2.8).

Based on the above mentioned points, an earlier study by Soares (2005) throws light on tyre influences as a problematic point, concluding that the effects of wide-based tyres (Figure 2.11) are greater than dual-based tires in initiating permanent deformation, which is converted to the pavement layers. It was also observed that the tensile strain due to wide-based tyres is 50% more than that of dual-based tyres.

Consequently, it was also noted that rutting initiated from wide-based tyres is 1.5 times larger than dual-based tyres on asphalt pavements.

Figure 2.11: Dual-based vs wide-based tyre (Soares 2005)

2.3.2.2 Climate Factors

Asphalt pavement layers undergo hot and cold circumstances which have influences on their behaviour. Therefore, through designing appropriate mixtures, pavement engineers attempt to decrease the environmental effects. Likewise, variable temperatures are the biggest factors in selecting layer thickness. As it is a visco-elastic material, bituminous materials tend to be more viscous in high temperatures, while the tendency of asphalt has changed to be more elastic in low temperatures. Furthermore, hot and cold temperatures are considered precisely in selecting suitable grades and types of binders, by evaluating significant functions and guidelines such as penetration, viscosity and aged residue (Lavin 2003).

The methods for design of asphalt mixtures are plentiful depending on different contributory factors: Marshall and Superpave mix design methods. According to Khan (2008), the central drawback of the Marshall Mix design is that in this method, changing temperatures, asphalt component properties and loads are not taken into account sufficiently. This procedure, however, is broadly used as a guideline in designing HMA. Besides, non-symmetrical temperatures brought a conclusion that these cases are more critical than the Superpave method as an example, which is seen as an efficient method for design.

Furthermore, high temperature is a contributory factor for rutting in asphalt leading it to be more viscous rather than elastic, while low temperatures have negative effects in cases of inclusion of moisture by aggregates leading to frost in the components, particularly in winter. Not only that, but cracks will eventually initiate in the asphalt layer, particularly as damage occurs. To eliminate high temperature effects, PMB is added to increase the elasticity of the mixture. Likewise, in cold weathers PMB is still used in addition to the increased usage of the binder in order to alleviate frost problems. This is particularly important in locations where cracks in asphalt tend to form due to increasing brittleness of the asphalt layers (Archilla and Madanat 2000).

Moreover, permanent deformation as one of the common distresses in roadways generally occurs. The dilemma of this situation is that there might have been vulnerable properties in one or some components which lead pavement layers to damage. Therefore, via using an appropriate mixture design, pavement engineers attempt to avoid or decrease the environmental effects. Likewise, variable temperatures are the largest factor in selecting layer thickness. More specifically, hot and cold temperatures are considered in choosing a suitable grade of asphalt binder and also the type of binder. With regard to the binders, there are significant measurements and guidelines for selecting binder type. These factors include penetration, viscosity and aged residue (Lavin 2003).

2.4 Stiffness Modulus

Previous research has proven that stiffness, as a mechanical property of the bituminous materials, is of high level of importance. Furthermore, in designing the main pavement layers, the designers pay a careful attention to include those materials of high stiffness. This property is usually of strong correlation with permanent deformation. In other words, using stiffer materials, specifically aggregate and proposed binders, tend to attain a survivable section of roads. Different layers illustrated in Figure 2.12 tend to carry diverse load severities, in which the generated stress on the upper layers may be more damaging to the surface layer followed by the binder layer within the bituminous layers; whereas the generated load in the base layer may be less than that of the uppers. This allows the maximum compressive strain at the top layers to be more effective, leading to generation of rutting deformation (Rahman 2004).

The elastic stiffness modulus in asphalt layers is considered to be an indication of the ability of bituminous layers associated with the utilized materials to spread the load over a road section. An acceptable stiffness spreads traffic load through a wider area (Figure 2.13). This leads to decreased strain levels generated lower down in the structure associated with the temperature and loading frequency. The stiffness modulus deserves great attention in terms of designing requirements of layer thickness in pavements, which generally can be determined in experimental works (ibid).

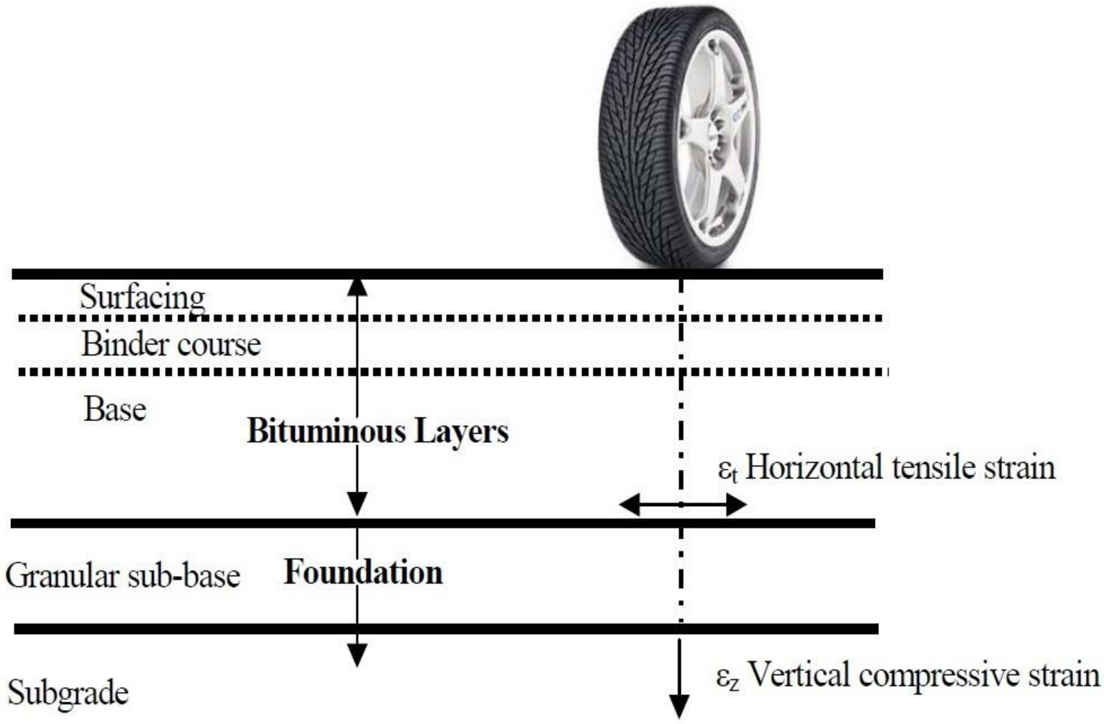


Figure 2.12: Flexible pavement structure (Rahman 2004)

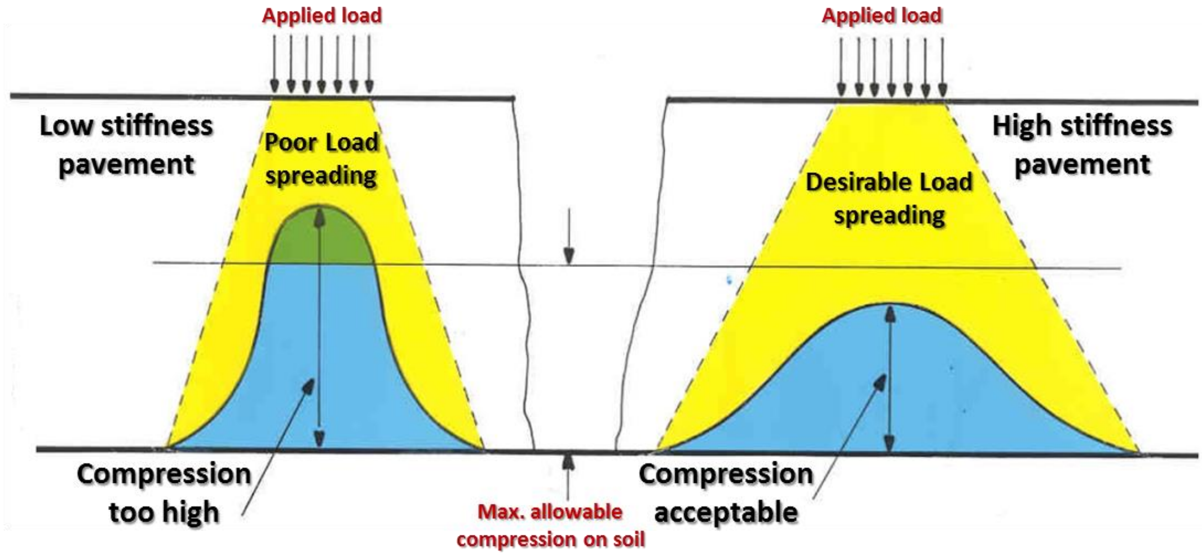


Figure 2.13: Load spreading in flexible pavement (Rahman 2004)

2.5 Polymer Modified Asphalt

Due to the fact that most developing mixtures within the conventional type of asphalt (HMA) are unable to resist non-recoverable deformation sufficiently, there is a great tendency towards adopting diverse types of polymers. This process is known as modified asphalt mixtures. It has been demonstrated practically that utilizing polymer modified binders demonstrates better rutting resistance compared with the conventional HMA (Robinson 2004; Lavin 2003; Tayfur et al. 2007).

2.5.1 Types of Polymers

In recent years, different types of polymers are still in extremely high demand. To meet the mechanical properties and sustainable goals, researchers have proposed a wide variety of polymers. Although, the overall performance of asphalt pavement has been underpinned with modifiers, it is crucial to identify the physical and chemical properties within the asphalt and binder. The nature of interaction between polymers and such a complex liquid like bitumen is yet to be fully understood (Robinson 2004; Lavin 2003). As a step-wise effort, according to Lavin (2003), polymers are divided into two parts identifying key relevant mechanical characteristics, such as long-term performance and viscosity of asphalt binders which are thermoplastic and thermoset. The first type is mostly soft when heated, and becomes hard in low temperatures, and this process can be repeated which is suitable for asphalt. Thermoset, on the other hand, has the ability to be hard when cooled but the process cannot be repeated, and it is soft in high temperatures. According to Robinson (2004), thermoplastic polymers can be categorized into elastomers, plastomers and natural rubber.

2.5.1.1 Elastomers

As a widespread type of polymer, elastomers are used as different types like synthetic thermoplastic rubber polymers, such as SBS, styrene butadiene rubber (SBR), styrene ethylene butadiene styrene (SEBS) and polybutadiene. Within these, one which has been receiving attention from pavement engineers is SBS (Figure 2.15). This may be related to its economy and performance within asphalt components, among other factors. Furthermore, SBS is able to improve the rheological properties of asphalt owing to the elastic response of the bitumen. This characteristic occurs after applying and removing elastic recovery (Figure 2.14). Meanwhile, viscous component is decreased after removing the applied stress. In reality, these two points are of importance in the modified binders in terms of permanent deformation due to repeated loads on the asphalt pavement (Robinson 2004). A similar study by Lavin (2003) reveals that despite the promising benefits of modified binders, the polymers should be added accurately. This is to achieve a suitable balance in the main components of bitumen (asphaltenes, resins, and maltenes). For instance, asphaltenes need maltenes to be present; without this balance, it may affect the binder’s workability.

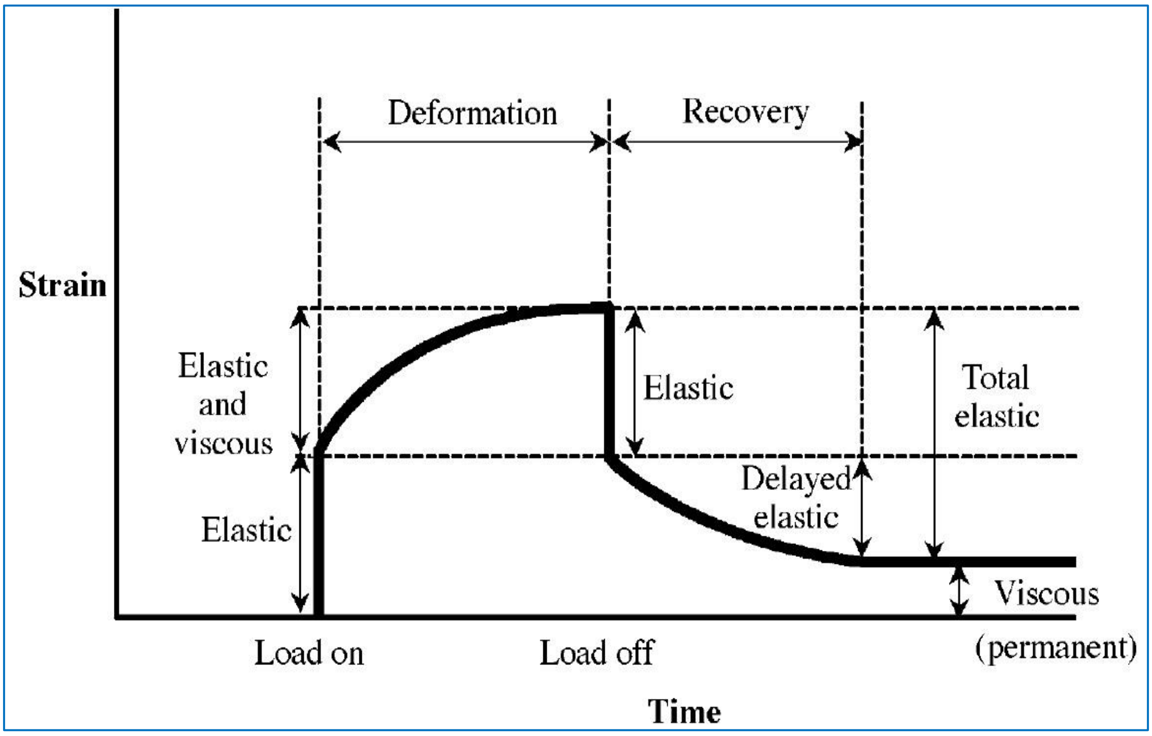


Figure 2.14: Bitumen permanent deformation model (Robinson 2004)

2.5.1.2 Plastomers

After elastomers, plastomers are highlighted as the second commonly used polymers, known as crystalline polymers, polypropylene, EVA, ethylene methyl acrylate (EMA) and polyvinyl chloride (PVC). It has been shown that viscosity or stiffness of the asphalt binder is increased noticeably, and thereby elasticity behaviour does not increase (Lavin 2003). Robinson (2004) states that decreasing the temperature sensitivity of bitumen is significant to reduce probability of rutting throughout hot summer seasons. Unlike elastomers, plastomers are less effective at lower temperature cracking. The most popular type of plastomer polymer is EVA, which is structurally random. This type is totally acceptable, offering an appropriate durability against repeated loads. Fundamentally, the working mechanism of this polymer is that during hot summers at high temperatures up to 100°C, the polymer efficiently melts and separates within the binder due to decreasing bitumen viscosity. Consequently, when the temperature gets cooler (below 90°C), the polymer tends to associate (recrystallize) and stiffens the bitumen, increasing the bitumen viscosity. To that end, it is important to ensure that the asphalt compacts completely before changing EVA phase starts; otherwise the asphalt may stiffen rapidly causing insufficient compaction, which may result in early failure.

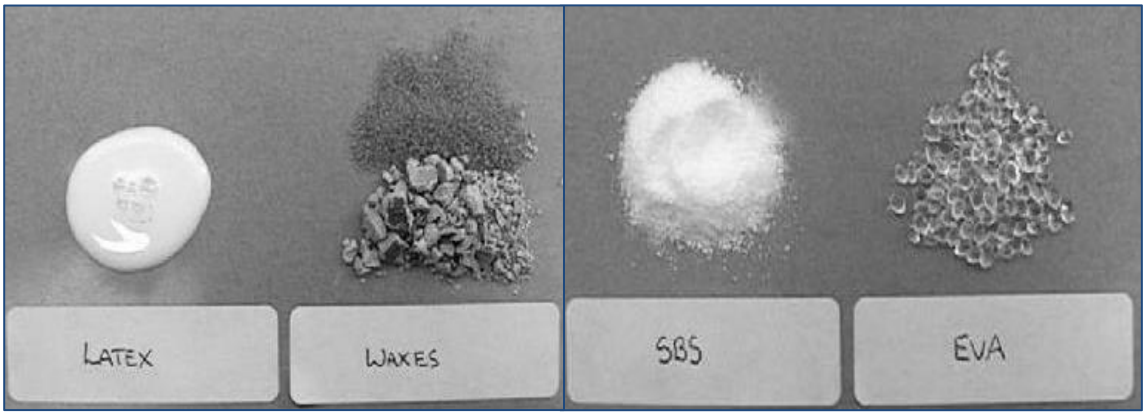


Figure 2.15: Different polymers used in asphalt (Robinson 2004).

2.5.1.3 Natural Rubber

From the past decades until now, there has been growing interest in using natural rubber latex in asphalt pavements to improve asphalt properties. In general, latexes (aqueous polymer) mixed directly into the asphalt, cannot modify asphalt performance to the same degree as elastomers or plastomers that have been mixed into hot binder. It has also been shown practically that mixtures modified by rubber indicate better rheological properties which are related strongly to permanent deformation. Using latex represents an applicable workability in plants when mixed directly into the asphalt mixer without using storage tanks. It is noted that the characterization of rubber latex is equivalently similar to synthetic thermoplastic polymers (Robinson 2004).

2.6 Microscopic Investigation of Polymers

To precisely understand the potential and functional properties of the polymer added to bitumen and asphalt, it is crucial to identify its characterization under the microscope, which is a considerably accurate task. Significant research has been done in this area by means of fluorescence microscopy to reliably evaluate this process. Sengoz and Isikyakar (2008) confirm that polymer in lower content samples indicate the existence of dispersed polymer components in a constant binder phase. Similarly, at high content, a continuous phase has been found for the same polymer. In this morphology study, image analysis recorded in SBS-modified bitumen that there is a noticeable variation in morphology, using different polymer contents. It was noted also at 5% polymer content, the polymer globules which are distributed by the base bitumen, well-matched fractions are arranged regularly in a constant bitumen phase (Figure 2.16).

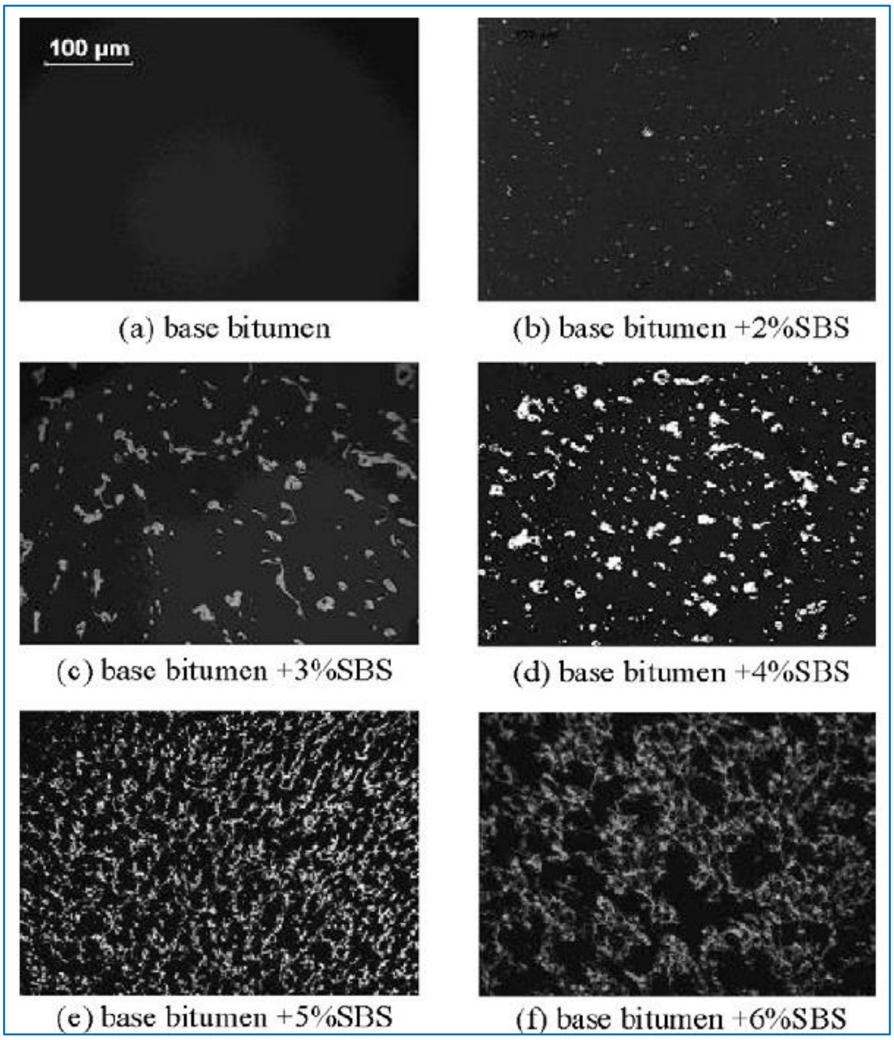


Figure 2.16: Fluorescent microscope view of SBS-modified bitumen (Sengoz and Isikyakar 2008)

Lu and Isacsson (2001) conclude that the essential properties of bitumen in terms of morphology, rheology and ageing entirely depend on modifier type, its content and nature of bitumen. Under fluorescent microscope, the rheological properties of bitumen improved in a high polymer content (5%) due to uniformly mixed particles of modifiers. It also appeared that using different thermoplastic or elastomer polymers (SBS, SEBS) and plastomers (EVA and EBA) in influencing ageing is temperature dependent.

2.7 Asphalt Mixtures with and without SBS Polymer Modification

Styrene-butadiene-styrene (well-known as SBS) is widely used in highway construction and by pavement engineers. The benefits of using SBS as a thermoplastic elastomer polymer are plentiful, depending on the applicable performance and properties within asphalt mixtures. Despite improving asphalt resistance against rutting, under laboratory temperatures, SBS can provide an appropriate stiffness in asphalt mixtures depending on its optimum rate, normally between 3% to 6%, which can also improve viscoelasticity and elongation. Consequently, adhesiveness, fatigue resistance, non-recoverable resistance and bleeding resistance could be improved. Therefore, it is preferable for it to be used exclusively for intersections, because in these areas high loading and slow traffic movements are constant (Roque et al. 2005).

Ping and Xiao (2009) support the above view by pointing out that SBS is able to soften HMA at low laboratory temperatures; likewise it can improve stiffness degree at high temperatures. Accordingly, these advantages may have an adequate influence in improving HMA performance in cold temperature thermal cracking, as well as in high temperature permanent deformation. To that end, it was demonstrated practically that SBS does not have an effect on tensile strength under indirect tensile testing.

An experimental study conducted by Khodaii and Mehrara (2009) concludes that mechanical properties, particularly permanent deformation of asphalt mixtures with and without SBS-modified mixtures, can be changed significantly by including coarse and dense graded mixtures. It appears, according to the results, that undertaking dynamic Creep tests (Figure 2.17) can indicate non-recoverable deformation, and that coarse grade-based mixtures generate less permanent deformation compared with dense grade-based mixtures, using different SBS contents (Figure 2.18a). More specifically, in between 4% and 6% SBS contents, it was noted that 5% SBS indicates an appropriate influence on permanent deformation (Figure 2.18b). However, it was found in Creep curves that lower stresses do not generate any effects in the test in modified mixtures.

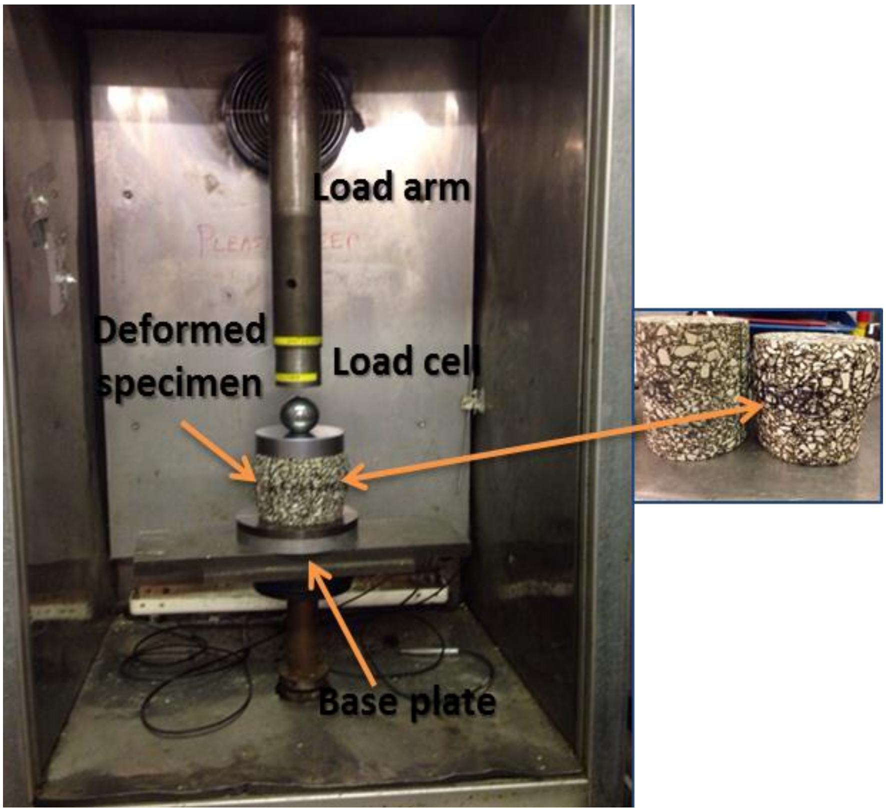
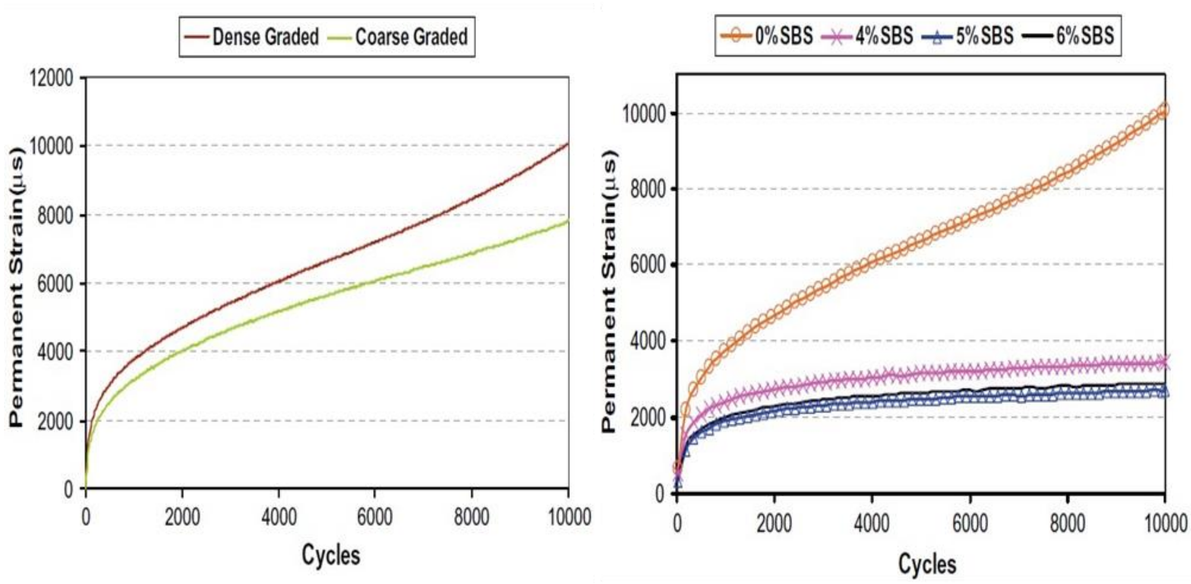


Figure 2.17: Deformed sample in Creep test, NTEC laboratory



(a) (b)

Figure 2.18: (a) Creep curves for unmodified coarse and dense-graded sand. (b) Creep curves or different contents of SBS-modified mixtures (Khodaii and Mehrara 2009)

Tayfur et al. (2007) report that performance of HMA could be improved, utilizing SBS polymers. This was verified experimentally by undertaking wheel tracking and dynamic Creep tests under various loading and temperatures. It was also demonstrated under indirect tensile tests that strength of modified asphalt mixtures are better than controlled samples. In other words, the tensile strength of modified mixtures seems to be more survivable to tensile strains and fatigue cracks that may lead to diverse cracks.

It seems that mixing other additives with the SBS polymer improves the mechanical properties of asphalt. Chen and Huang (2007) reveal that mixing sulphur with SBS can increase the elastic recovery of asphalt. Likewise, adding different percentage contents of sulphur into SBS can increase the softening point, whereas penetration can be decreased. Similarly, Al-Hadidy and Tan (2009) found that mixing SBS with starch (ST) modified mixtures could prevent moisture damage and temperature effects, despite improving the above mentioned properties.

2.8 Standard Evaluation and Testing Methods

2.8.1 Multiple Stress Creep Recovery Test (MSCRT) for Bitumen

Dynamic Shear Rheometer (DSR) is used for assessing a binder's elastic response to permanent deformation. An acceptable elasticity in binders may perform rather similarly to elasticity in mixtures (Figure 2.19), or may not be satisfied because of aggregate contributions. This is related to the behaviour of the main asphalt components (Golalipour 2011). The MSCRT is carried out by applying a 1 second creep stress followed by 9 second recovery for binder sample. In the MSCRT % recovery strain can be measured, in which the effect of J_{nr} can be determined, which is a non-recoverable compliance. This is quite relative to rutting indication. Therefore, this test is strongly preferable to demonstrate permanent deformation performance; for example, reducing the compliance (J_{nr}) by half decreases rutting by such an equivalent value. Additionally, this test is undertaken on the same equipment as DSR test. The DSR test is used to find the rheological properties of binder as explained in Appendix A.

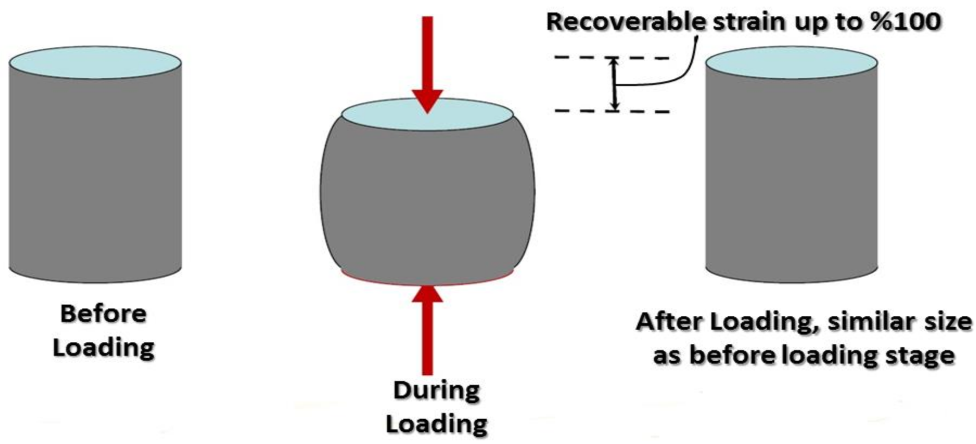


Figure 2.19: Conceptual representation of a typical elasticity response

An experimental study by Zoorob et al. (2012) shows that the polymer modified bitumen with SBS can perform better resistance under shear stress in comparison with pen bitumen. In other words, the creep compliance (J_{nr}) indicates better resistance of PMB with loading time during MSCRT at 73 °C under 800 Pa of shear stress compared with other pen binders including different grades and temperatures (Figure 2.20). Full details of the MSCRT can be seen in chapter four and Appendix C.1 for further detailed procedures.

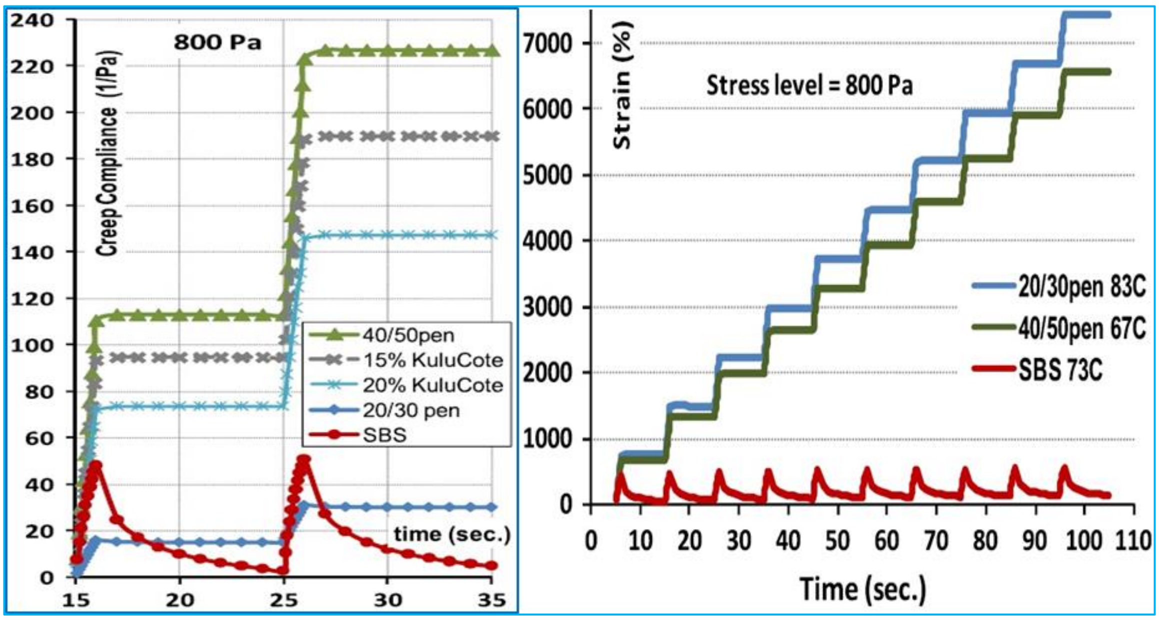


Figure 2.20: Illustration of creep compliance and strain (%) versus time using SBS and different conditions of Pen bitumen (Zoorob et al. 2012).

2.8.2 Wheel Tracking Test (WTT) for Mixtures

One of the most efficient tests for assessing permanent deformation is the wheel tracking test. Several studies have been conducted to evaluate rutting performance for unmodified and modified asphalt mixtures. The majority of these efforts have focused on using different ways of wheel tracking devices. It appears that there has been systematic consideration for developing this test using different wheel sizes and samples. Generally, the mechanism in working the wheel tracker is that the machine is fixed on a table and the repeated movements from the wheel on the sample are applied forwards and backwards continuously. This test is undertaken at room temperature, under the applied load of the solid tyre (Table 2.2). The tyre passes repeatedly on the prepared sample, where initiating rutting depths can be measured depending on types of mixtures (Garba 2012; Moses 2011; Tatic et al. 2006).

Table 2.2: Wheel tracking test conditions (Khan 2008)

Mix Type	Temperature(^{0}C)	Wheel Tracking Test
Marshall SMA Superpave	25	No. of Passes = 10,000
	40	
	55	

Tayfur et al. (2007) highlighted that modified mixtures can decrease rutting depth under comparable circumstances (Figure 2.21). An experiment based study by Khan (2008) illustrated that rutting depth can be increased by raising temperatures and the number of passes under the wheel trucker utilizing HMA and Superpave samples. However, it was noted that rutting depth in the Superpave is less than its counterparts. This method was developed by SHRP (Strategic Highway Research Program) which has a new binder grading method, for low and high temperatures together, and a new mix design of aggregates using fine and coarse in sizes and angularity in shapes which represent better durability compared with marshal method.

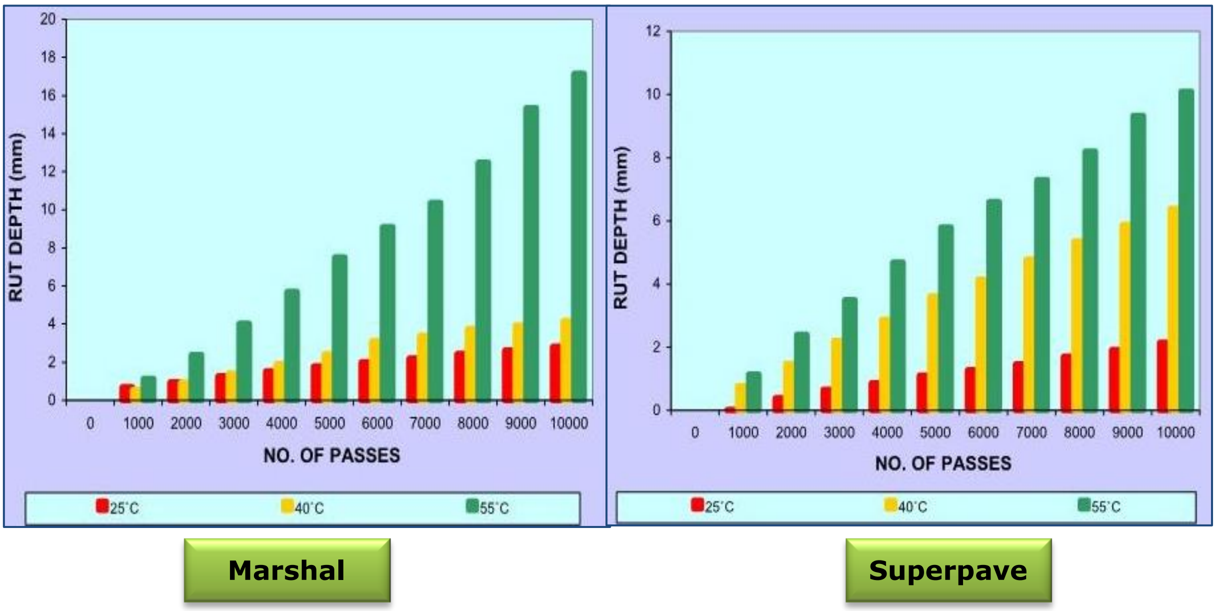


Figure 2.21: Rut depth for Marshall and Superpave mixtures (Khan 2008)

2.9 CONCLUSIONS

Permanent deformations have been investigated in detail and critically numerous studies reviewed, including the fundamental key factors encountered during this literature review. The essential mechanisms regarding rutting initiation can be highlighted as rutting due to densification and shear failures. The contributing factors apparently associated with structural and non-structural factors have also been discussed. As evidenced in the literature review, aggregate and binder properties can play a vital role in asphalt mixtures.

As aforementioned, it appears also that repeated loads from traffic may lead to asphalt pavements rutting with different severities. Tyre sizes and shapes of trucks may also generate damages on roads, especially on the contact areas. Although finding a concrete solution for rutting, is not an easy task, it is highly suggested based on experimental studies, that modified mixtures are utilized in order to design durable asphalt mixtures, for diverse environmental and loading circumstances; taking into account long-term service life of the bituminous materials. Under these circumstances, different polymers were identified, investigating the main properties including polymer behaviour with itself and binders under microscopic views.

Since permanent deformations are highlighted in previous studies to be further explored, measurements are still being refined and are becoming more objective. In light of previous literatures, it seems that it is necessary to further investigate optimum SBS-modifiers within HMA proportions. Therefore, from these perspectives, the present study is particularly interested in the following tasks for the experimental approaches:

1. Designing asphalt mixtures, using the HMA method with different percentages of SBS-modified polymer and control samples, to reach the optimum target of predicting rutting performance. The prepared mixtures should undergo evaluation in the following laboratory tests to find out the effect of SBS on the rutting performance of asphalt binders and mixtures.

- Multiple Stress Creep Recovery Test (MSCRT): To investigate bitumen resistance for rutting using different percentages of SBS-modifier and control binder.
- Indirect Tensile Stiffness Modulus Test (ITSMT): To find out stiffness of the mixture samples.

- Wheel Tracking Test (WTT): To find rut depth for mixture slabs.
- Repeated Load Axial Test (RLAT): To determine axial strain percentages for mixture specimens.

2. The results could be used as a base to design asphalt mixtures for different layers. Thereby, assessing how best to incorporate preferred SBS-modified mixtures into mix variations. Thus, it is possible to determine an improved model for permanent deformation using SBS-modified asphalt mixtures. This means that long-term expected service life of asphalt pavement can be extended with using SBS polymer.

CHAPTER THREE: MATERIALS AND METHODS

3.0 Overview

The mixtures designed in this study were prepared for the surface layer, which requires specific particle sizes of aggregate, although the aggregate was the unchanged part in this project. Likewise, the utilized binder was designed to be appropriate for the typical climate in the Kurdistan region in terms of penetration grade (Pen 40/60). Moreover, the additive (SBS) was appropriate for a high temperature, which is the case in this region, particularly for permanent deformation as proven in the literature review. The optimum binder was attained after trial and error using different types of aggregate (Table 3.1); these were lime stone particles, which were at first rejected, and then changed to granite. To reach a reasonably acceptable air void content, it was apparent that granite can provide a more preferable air void content for the desired mixtures. This chapter presents the whole operation of material selection and sample fabrication and distribution, while further details of mixture proportions and their properties are presented in Appendix B.

3.1 Material Selection and Sample Fabrication

Specifically, the materials proposed to carry out this project were designed to be used for the surface layer of flexible pavements. Therefore, careful attention has been paid to the material selection and the main asphalt mixture components, so that the most appropriate materials were used in order to attain as much resistance as desired against permanent deformation. Additionally, the mixture has to be considered to be reasonably economical, such as in terms of binder content and SBS percentages. Likewise, the workability of the asphalt mixture components has been considered seriously, with regard to the weight of aggregates with an appropriate binder grade and percentages of polymers by mass of binder to be blended. Moreover, the accuracy of the batching process and the conditions of the materials were also considered. The logical order of the sample fabrication, which was applied in this experimental study, is outlined below:

- **Select binder content and grade**
- **Aggregate gradation**
- **Batching process**
- **Blending process**
- **Mixing**
- **Compaction**
- **Conditioning.**

3.1.1 Selecting Binder Content and Grade

The most important point to consider for HMA to be reasonably well designed is to choose an appropriate binder content and suitable grade for the binder. In many poorly designed mixtures, the low binder contents generate poor workability, leading to increased brittleness of the asphalt mixtures, which may cause fatigue cracks; while high bitumen contents lead the mixture to bleeding, which may consequently generate permanent deformation due to the tendency of the mixture toward high viscosity. Therefore, it is difficult to design a perfect mixture guaranteeing against the risk of both of the above mentioned characteristics (fatigue and rutting). In this case, what is important is to choose an optimum binder content for the mixture. That is what this research project considered in terms of binder content, which was found experimentally to be 5.1% added by mass.

With regard to the selected grade, if it is inappropriately designed it may not be survivable at the existing temperatures, which means it would not safely fulfil its role of supporting repeated traffic loads. Not only that, but cracks or permanent deformation will eventually initiate in the asphalt, particularly as damage occurs. For example, stiffer binder grades are desirable for eliminating the risk of rutting and bleeding, whereas for cold temperatures, a less stiff binder is appropriate to eliminate the risk of cracking problems. For that reason, in this project, the binder content and the grade that were used considered the environmental conditions of the Middle East, or more specifically, the Iraqi Kurdistan region, which has considerably rather high temperatures. Thus, it was decided to choose a 40/60 pen binder to be used in manufacturing nine slabs including SBS-modified bitumen. This particular grade is reasonably appropriate for the region.

As illustrated in Table 3.1, according to BS EN 4987-1 (2009), the bitumen content was constant at 5.1% by mass for modified and unmodified binders. The binder was heated up to 180°C to be mixed with the heated aggregate in the mixing process, in order to provide maximum density for the mixture to gain the target density, which was 2,457 Kg/m^3. In cases of using this particular bitumen content, which is considered as a typical percentage, there were no coating problems with the aggregate during the mixing process.

Table 3.1: Bitumen content for 0/14 mm size close graded surface course (BS EN 4987-1 2009)

Aggregate	Bitumen grade
	% by mass of total mixture (±0.5 %)
Crushed rock (excluding limestone)	5.1
Limestone	4.9
Blast furnace slag of bulk density in Mg/m^3	
1.44	5.5
1.36	6.0
1.28	6.6
1.20	7.0
1.12	7.5
Steel slag	4.8
Gravel	—

3.1.2 Aggregate Gradation

To achieve reasonably appropriate particle sizes of aggregate, gradation of aggregate is a standard method that was carried out to design the desired particle sizes. The aggregate used for the experimental programme was designed to be used for the surface layer, or as more commonly known, wearing course. This layer is more likely to be exposed to deteriorations due to high, uncontrolled traffic loads and climate factors, explained in detail in the literature review (section 2.3). Usually, the particle sizes used in surface layers tend to be mostly fine, which provide better rutting resistance. For the surface layer, the nominal maximum aggregate size (NMAS) is typically indicated by the designer and is associated with the thickness of the asphalt mixture (Kim et al. 2009).

Different types of aggregate with different particle sizes and shapes present different behaviours in terms of resistance. Furthermore, it has been determined experimentally that Virgin Crushed Limestone (VCL) particles provide a high air void content for the mixture, whereas crushed granite particle sizes, known as bardon in pavement terminology, result in a reasonably suitable void content (5%). Based on the outcome of the trial and error attempts, it was decided to utilize a granite type aggregate for the designed job mix in this study. The upper line of the gradation curve illustrated in Figure 3.2 represents fine materials, whereas the lower line represents course materials as percentage of passing decreases. The variable line drawn between both lines represents diversity in terms of particle sizes (Tables 3.2 and 3.3). The designed particle sizes for this project utilized for manufacturing the samples were 14 mm, 10mm and 6.3 mm, plus dust and filler; while the nominal maximum particle size is 14 mm, the filler has the minimum particle size (Figure 3.1).

Table 3.2: Aggregate grading for 0/14 mm size close graded surface course (BS EN 4987-1 2009)

Test sieve aperture size mm	Indicative FPC tolerance[a]	Aggregate: crushed rock, slag or gravel % by mass passing
20		100
14	– 8/+ 5	95–100
10	±7	70–90
6.3	±7	45–65
4	±7	Report value[b]
2	±6	19–37
1	±4	10–30
0.063	±2	3–8

Table 3.3: Determination of the percentage passing using mid-size aggregate

Blending Table										
Sieve	**13-1206**	**13-1205**	**13-1204**	**07-695**	**07-694**		**Total %Passing**	**Specification**		
Percentages	0	24	30	11	34	1	100	Lower	Mid	Upper
	20 mm	14 mm	10 mm	6 mm	Dust	Filler				
20	0	24	30	11	34	1	100.0	100	100	100
14	0	21.276	29.895	11	34	1	97.2	95	97.5	100
10	0	5.9592	28.002	11	34	1	80.0	70	80	90
6.3	0	1.0776	9.117	9.8934	34	1	55.1	45	55	65
2	0	0.4944	1.05	0.6963	25.7482	1	29.0	19	28	37
1	0	0.4656	0.747	0.4334	16.2928	1	18.9	10	20	30
0.063	0	0.3288	0.489	0.2651	3.3422	1	5.4	3	5.5	8

Figure 3.1: Illustration of the designed aggregate particle sizes

Ideally, in order for the right design, it is often necessary to consider the availability of the materials in terms of their economic aspects. The materials in the diverse layers, not only from the surface, have to be ensured to be available on site. Fortunately, there are considerable sources of this type of aggregate and it is of high level in the Kurdistan region.

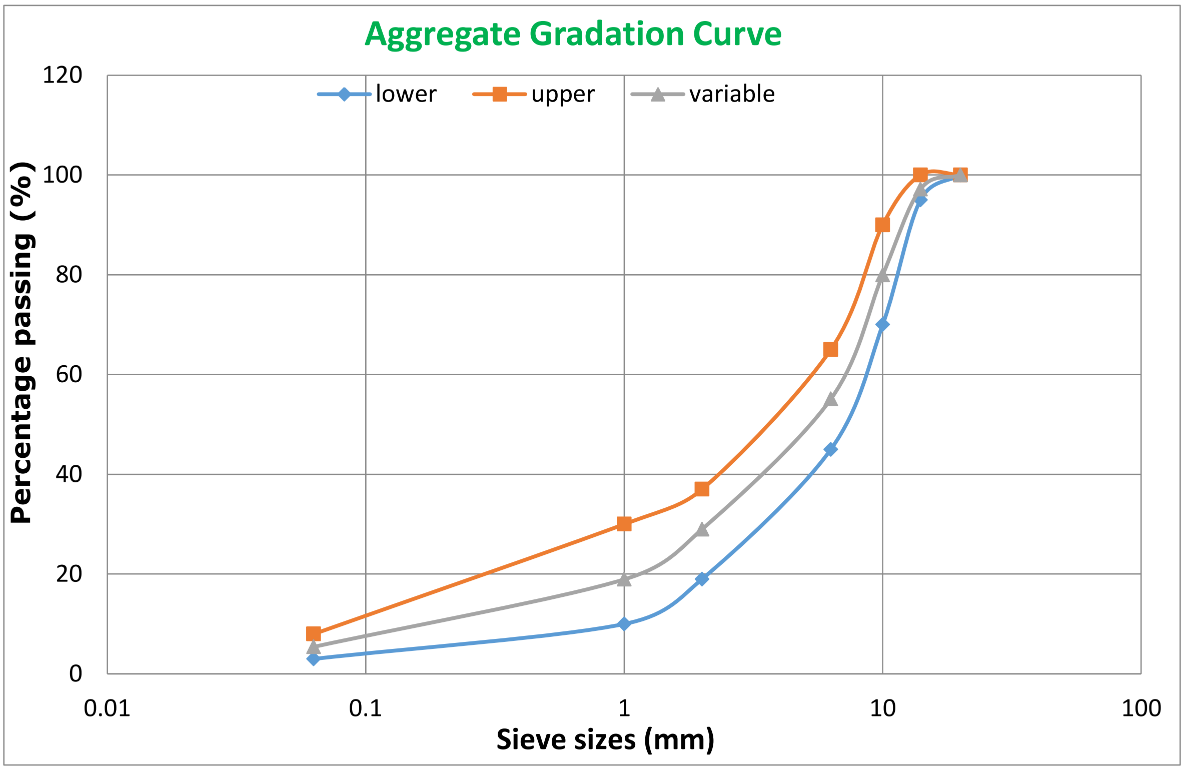


Figure 3.2: Illustration of the gradation curve for aggregate particle sizes

3.1.3 SBS-Modifier

This experiment based study proposed SBS polymer to be used in different percentages by mass of binder. As explained in the literature review (section 2.5) SBS has advantages over the other polymers in that a considerable elasticity performance can be achieved under high temperature circumstances. Furthermore, it is also a fairly supportive process by offering a recovery characteristic to the bituminous mixtures after any load cycle owing to repeated traffic loadings. The most significant point to highlight is that it has to be carefully added to the binder before mixing with the aggregate. If not, this can lead to inconsistent designs, where, inevitably, some designs will be too costly and other designs will be too impractical or unworkable (Kim 2010).

This project took into account three different percentages of SBS (3%, 5% and 7%) by binder mass and base binder to be mixed with the binder. In this case, a question may arise as to why these particularly close percentages are exclusively used. Firstly, SBS is considered an expensive type of polymer. Secondly, the key point as opposed to the ideal one is that when the results bring to light slightly close but different resistances between each percentage, one can then decide to use the optimum percentage, which is more likely to be the most economic. In addition, the typical properties of utilized SBS-modifier are it is a solid, white colour (Figure 3.3), essentially odourless (after mixing there is almost an odour) with density 880-950 kg/m^3 and it is soluble in water (specific gravity <1).

Figure 3.3: Typical SBS-modifier

3.2 Specimen Fabrication Process

In order to carry out four tests as proposed (MSCRT, WTT, ITSMT and RLAT), it was decided to manufacture nine slabs (305mm x 305mm x 60mm) to be used for the tests as a flow approach in fulfilling the three mixture tests. This is considered to be an efficient way of manufacturing an economic number of samples to be implemented, because they were used to undertake different tests, and even more if there were not a limited scope for this study in terms of the number of tests.

3.2.1 Blending Process

After selecting the binder content and its grade, as well as the polymer type including different percentages (3%, 5% and 7%) of SBS, the blending process was carried out at a temperature of 180 °C (170°C to 190°C are the limit for SBS-modified bitumen) for the three different percentages, including the actual masses, under a heating period of 150 minutes (Figure 3.4).

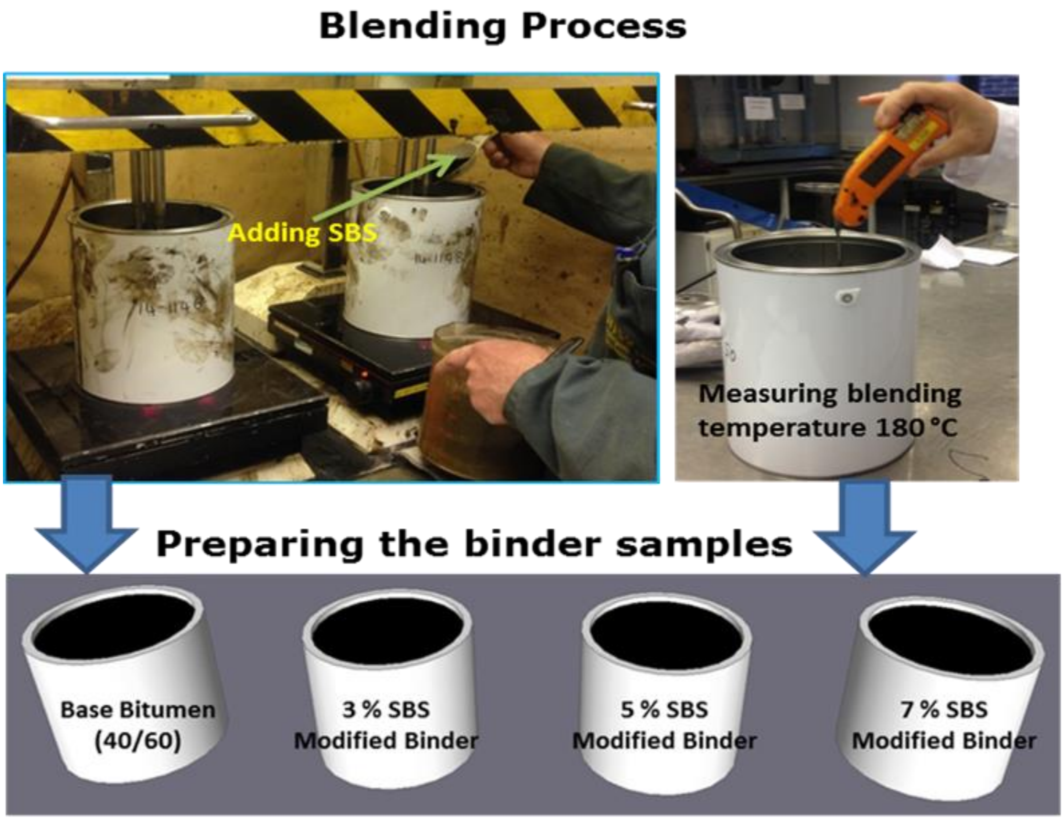


Figure 3.4: Blending process

3.2.2 Batching Process

The particle sizes of aggregate implemented in the gradation process (14 mm, 10mm, 6.3 mm, dust and filler) were weighed in the batching process (Figure 3.5) for each sample (nine slabs) in a repeated process, to be constant in this study. Essentially, the consideration of loss in the mixture was determined mathematically before batching. The weighed samples underwent conditioning in the oven (180 °C) to be ready for the mixing process.

Figure 3.5: Batching process for aggregate

3.2.3 Mixing

This process had to be carefully implemented. The prepared materials, aggregate and binder (base binder and polymer modified binder), were mixed for each slab mould, which were under conditioned circumstances according to specifications. The mixing process for each mixture was carried out inside the mixer at 180°C (Figure 3.6). An automated process was undertaken to ensure uniform mixing until the aggregate was totally coated with the binder.

Figure 3.6: Mixing process and sampling

3.2.4 Sampling and Compaction

After the mixing process, each mixture was poured into a slab mould until the desired dimension (60 mm thickness) was reached and was covered with a piece of paper to avoid asphalt sticking to the roller surface. The wheel passes representing the roller compacter was applied in four stages of 10 cycles with 2 bars of pressure for the first stage. The compaction was increased by increasing the pressure to 5 bars and 10 passes in the second stage, while from the third stage; the number of wheel passes was reduced to 5 and 4 bars of pressure. In the fourth stage the sample was compacted with 3 bars of pressure and 5 wheel passes to gain the designed void content of the mixture (around 5%) for each slab under the same temperature as mixing using the roller compacter, which is commonly used for hot rolled asphalt (HRA) mixtures (Figure 3.7).

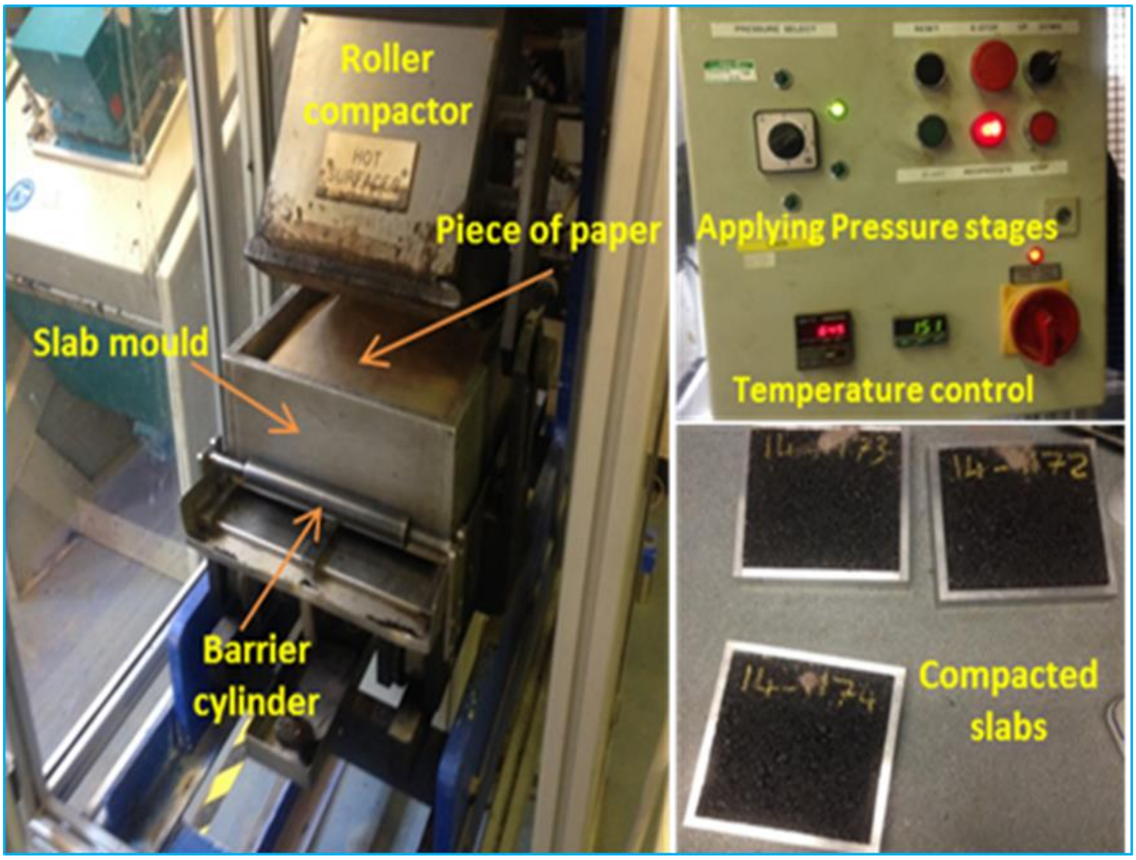


Figure 3.7: Compaction of slabs using hot rolled asphalt (HRA) mixture compactor

3.2.5 Sample Managing and Distributions for the Tests

Initially, the same blending source was used to take samples for the MSCRT associated with the binder including PMB and the base binder. As aforementioned, nine slabs were manufactured for the mixtures for WTT, in which three of them were conventional mixtures, while the other six slabs were the modified asphalt mixtures, so that every two slabs represented one particular percentage (3%, 5% and 7%) as shown in Figure 3.8 below. From the nine slabs, two cores were taken per each slab, which means six from the three conventional slabs and twelve from the polymer modified mixtures (four cores per each percentage of SBS-modified mixtures). The cored specimens were used for other two mixture tests (ITSMT and RLAT respectively) as shown in Figure 3.9 following foil method for determination of the void content in the mixtures explained in chapter four. Although there were some drawbacks generated by this approach of sample managing and distributions, it is fair to mention that this was an appropriate approach economically and better from a safety point of view, as the specimens were manufactured only as one set of slabs and after WTT, the samples were cored for the NAT (Nottingham Asphalt Tester) tests.

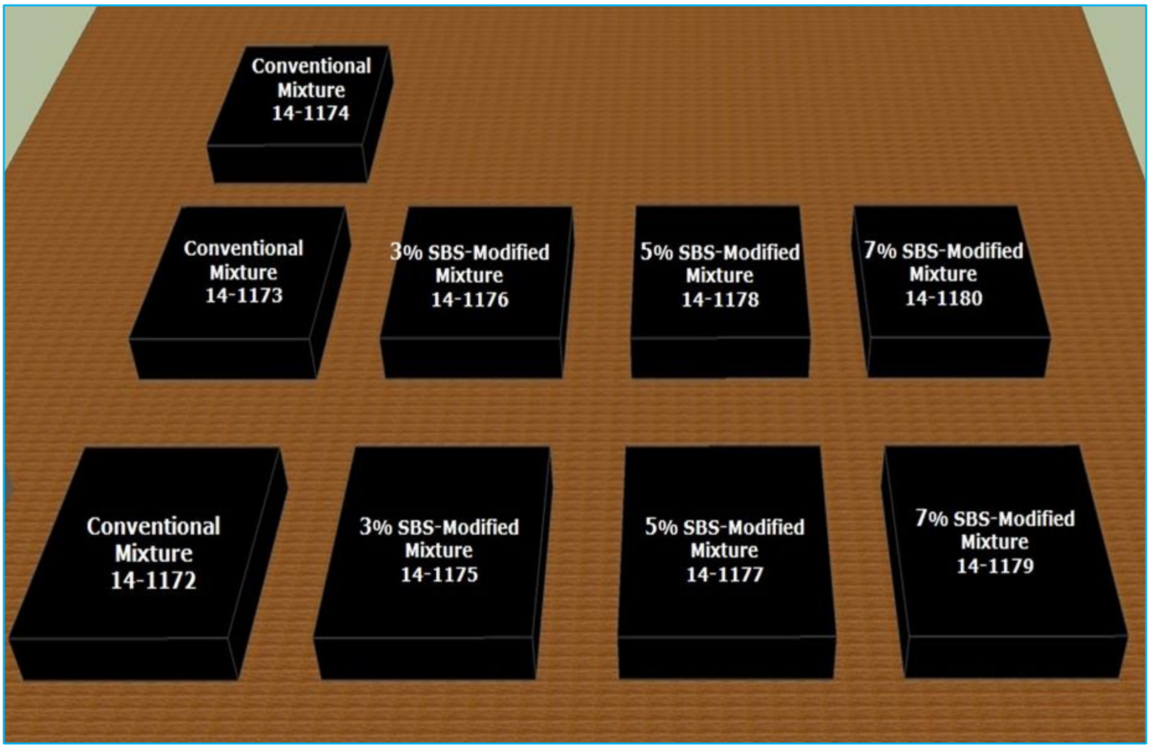


Figure 3.8: Model illustration of specimen distribution for WTT

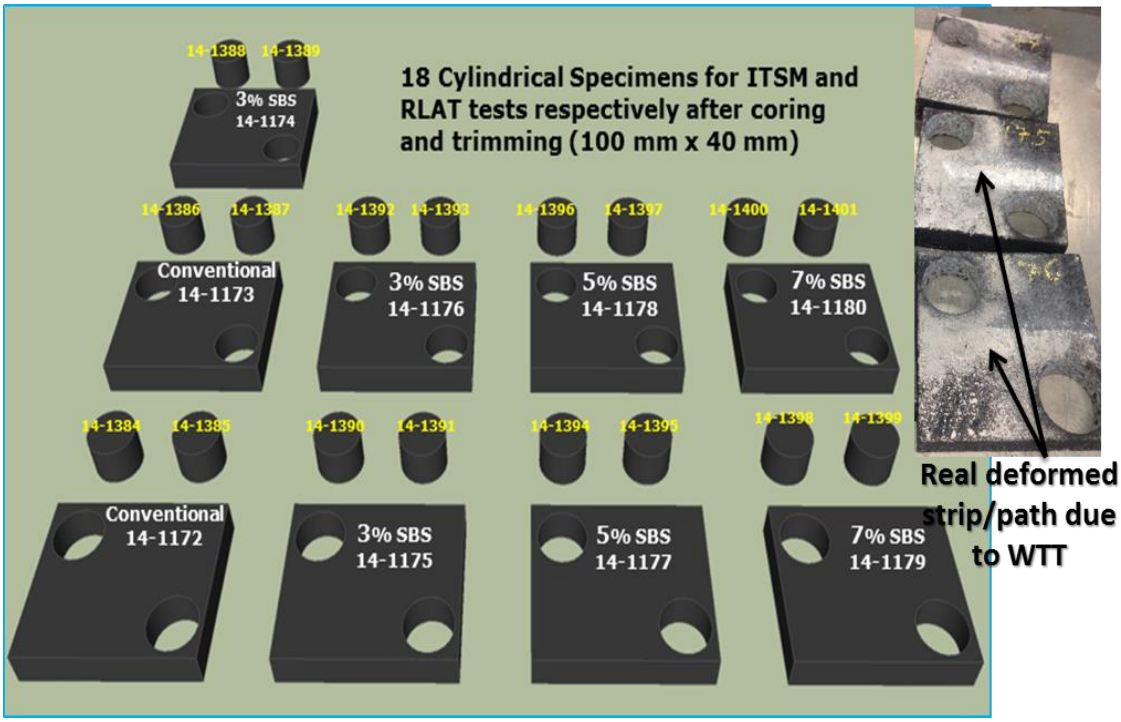


Figure 3.9: Model illustration of specimen distribution for ITSMT and RLAT

3.3 Summary of Key Points

It can be summarized that due to careful selection of the main components of mixtures volumetrically, the specimen preparation was carried out reasonably acceptably. The key point from this task is that the possibility of inconsistent outcome might be expected due to influence of quality control associated with the material types and sample preparation methodology. In other words, this project was designed to include considerably close percentages of SBS, which means any small variation during specimen fabrications might change the targeted approach of the results significantly, particularly the optimum percentage of SBS, which is of great consideration for this research project.

CHAPTER FOUR: EXPERIMENTAL PROGRAMME

4.0 Overview

To achieve the fundamental goal of this research project, it was considered that the most important and foremost tests, which are strongly related with permanent deformation, were carried out. The outcome generated from the undertaken tests should be more relative and remarkably realistic for rutting performance of bitumen and asphalt mixtures to be interpreted and investigated. In this study, four tests were undertaken; MSCRT to assess the proposed binder after the blending process, plus three other tests to examine and evaluate the designed mixtures, including modified and unmodified. The three mixture tests are WTT, ITSMT and RLAT respectively. Before that, foil method was carried out to find the void content of the mixture samples as representative for each mixture including those with different polymer percentages. Most importantly, prior to undertaking each test, a risk assessment was taken into account to eliminate any risk during the test for the experimenter, or even for technician staff. A copy of the risk assessments is evidenced in Appendix E.

4.1 Air Void Content Determination Methods

Fundamentally, as outlined below, there are several methods for the determination of air void content of asphalt mixtures:

4.1.1 Gyratory Compactor method

This method was proposed by SHRP to be used in the Superpave design method. This is considered by pavement authorities to be a more realistic and accurate method, which is more reliable, because it is considerably, reflects the real circumstances in terms of what occurs within asphalt mixtures owing to diverse traffic conditions.

4.1.2 Marshal Method

This is also still widely used, despite the limitation of being unrealistic in terms of the compaction method, which depends on the number of blows to gain the desired compaction.

4.1.3 Dimension Method

This is a simple and fast method, which basically depends on the known mass and the dimensions of the specimens in order to find out the volume. Thus, the density of the mixture can be found. Meanwhile, the maximum density of the mixture is also determined prior to this stage, during the mixture design stage. Therefore, the void content of the mixtures can be determined mathematically. The only drawback is that this method is not so accurate, which means that it is preferable if there were no possible choices.

4.1.4 Water Content Method

This is also a widely used method, which depends on the dry and wet mass of the sample in water. Mathematically, the air void content is calculated, which may be (as in the dimension method) not so accurate.

4.1.5 Foil Method

There was no method available to determine air void content of the mixtures using equipment such as a gyratory compactor (which was not used in the sample preparation because of the use of slabs); therefore, this project focused on the 'foil method', which is an efficient approach for finding air void content of mixtures (Figure 4.1). This is considered to be the most accurate method among the above mentioned methods for air void determinations. It was utilized before carrying out the mixture tests because using gyratory compaction was impossible due to the way of manufacturing the samples. As it was impractical to determine the air void content of the slab, the best possible approach was to use the mean value of four cores to obtain the air void content for the type of mixture for the slabs. Although this might not be entirely accurate for representing the density of each mixture type, the proposed method is the only solution that can be implemented.

In this method three diverse weights were taken for the specimens to be representative for the entire mixtures (Table 4.1) as described below:

m_1: Mass of the specimen in air (g)
m_2: Mass of the specimen in air sealed with foil (g)
m_3: Mass of the specimen in water sealed with foil (g)

After weighing the specimens, the density of water (ρ_w) is assumed to be 1 Mg/m^3. Meanwhile, the relative density of foil should be known, which in this project was 1.581 Mg/m^3. Thus, the three masses are used in the following formula according to BS EN 12697-6 (2012) to determine the bulk density:

$$Bulk\ Density = \frac{m1}{[\left(\frac{m2-m3}{\rho w}\right)-\left(\frac{m2-m1}{\rho w}\right)]} \qquad (4.1)$$

Therefore, by following the formula, percentage of air void content (%) for the mixture can be determined in order to be compared with the designed air void content of the mixture:

$$Air\ Void\ content\ \%\ of\ mixture\ (Vv) = (\frac{\rho max - \rho Bulk}{\rho max}) * 100 \qquad (4.2)$$

Table 4.1: Illustration of the foil method requirements

Sample Number	Mass of sample in air (g) m_1	Mass of sample in air sealed foil (g) m_2	Mass of sample in water, sealed in foil (g) m_3	Density of water (assumed) (Mg/m^3)	Relative density of foil (Mg/m^3)
14-1384	760.3	766.4	448	1	1.581
14-1385	773.1	779.7	457.9	1	1.581
14-1386	728.2	734.4	427.6	1	1.581
14-1387	760	765.5	451.4	1	1.581
14-1388	745.3	751.3	445.9	1	1.581
14-1389	749.3	755.6	444.8	1	1.581
14-1390	793.8	800.5	476.7	1	1.581
14-1391	767.6	775.2	455.8	1	1.581
14-1392	754	760.2	440.1	1	1.581
14-1393	733.2	740.2	424.6	1	1.581
14-1394	806.1	812.4	486.1	1	1.581
14-1395	780.5	786.4	462.7	1	1.581
14-1396	784.5	790.7	468.7	1	1.581
14-1397	781	788	462.5	1	1.581
14-1398	771.4	777.5	453.9	1	1.581
14-1399	784.1	790.2	469.7	1	1.581
14-1400	786.1	791.9	469.2	1	1.581
14-1401	790.4	796.2	468	1	1.581

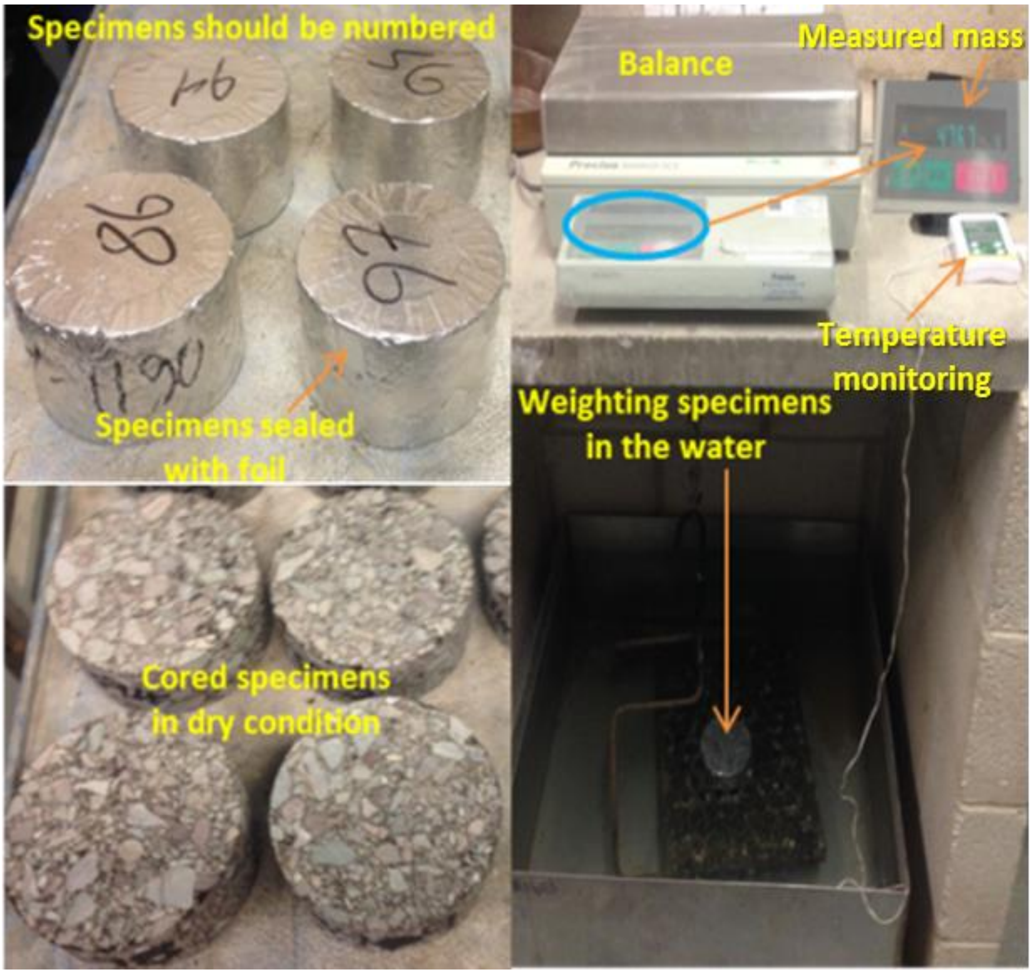


Figure 4.1: Foil method for the determination of air void content of the mixtures

4.2 Multiple Stress Creep Recovery Test (MSCRT)

Fundamentally, this test is used to assess the permanent deformation performance of binders. This is also suitable for polymer based binders to indicate the performance of the binder at different temperatures. This can also allow determination of the optimum polymer content without using mixture tests, which means that a much more economic use of polymers may be indicated to improve performance. Interestingly, this test needs relatively less time to be performed in laboratory conditions, which is considerably more applicable in use. Experimentally, it has been proven that MSCR is considered to be the most accurate test for the prediction of rutting susceptibility (Golalipour 2011).

4.2.1 The Main Parameters

DSR equipment depends on creep and recovery methods in order to find the percentage of recovery (%R) and non-recoverable creep compliance (J_{nr}), which are two of the parameters calculated from the measured strain under different stress cycles by applying creep stresses to assess the elastic behaviour of binder samples. In terms of simplicity, small software changes are required to carry out the test. As the same equipment is used, sample preparation is quite similar to the DSR test. Non-recoverable compliance (J_{nr}) is the main parameter for representing rutting susceptibility for binders. The most frequent stress levels that have been used in previous studies are normally two, i.e. 0.1 kPa and 3.2 kPa respectively. Experimentally, the present research considers eleven stress levels to be used in order to obtain a comprehensive outcome for evaluating rutting susceptibility. Stress levels up to eleven have not been widely used in previous studies because of the complexity of the work. Usually, two stress levels have been considered. The test uses a one second creep loading followed by nine seconds upon instantaneous unloading for the following stress levels: 0.25, 0.50, 0.100, 0.200, 0.400, 0.800, 1.600, 3.200, 6.400, 12.800 and 25.600 kPa at 10 cycles per stress. Likewise, three different temperatures (50°C, 60°C and 70°C) have been used, with a temperature of 60°C repeated twice due to uncertainty in the obtained results.

4.2.2 The Main Procedure

1. This test was performed according to ASTMT D7405−10a (2013) using DSR equipment, which has been prepared for the desired condition in this project (Figure 4.2).
2. Specimen preparation was carried out on the same blending source of the modified binders (unaged binder) including three different percentages of SBS (3%, 5% and 7%). Likewise, the grade of the binder was the same grade as that of the mixture tests (40/60) as it was from the same source.
3. Bitumen samples underwent a conditioning process 15 minute prior to the test at 160°C.
4. The specimen was loaded after pouring on the base plate using a hot process, under application of a constant creep stress of 0.100 kPa, for a one second duration creep, followed with a zero stress recovery for nine seconds (Figure 4.3).

Figure 4.2: DSR apparatus available at NTEC Laboratory

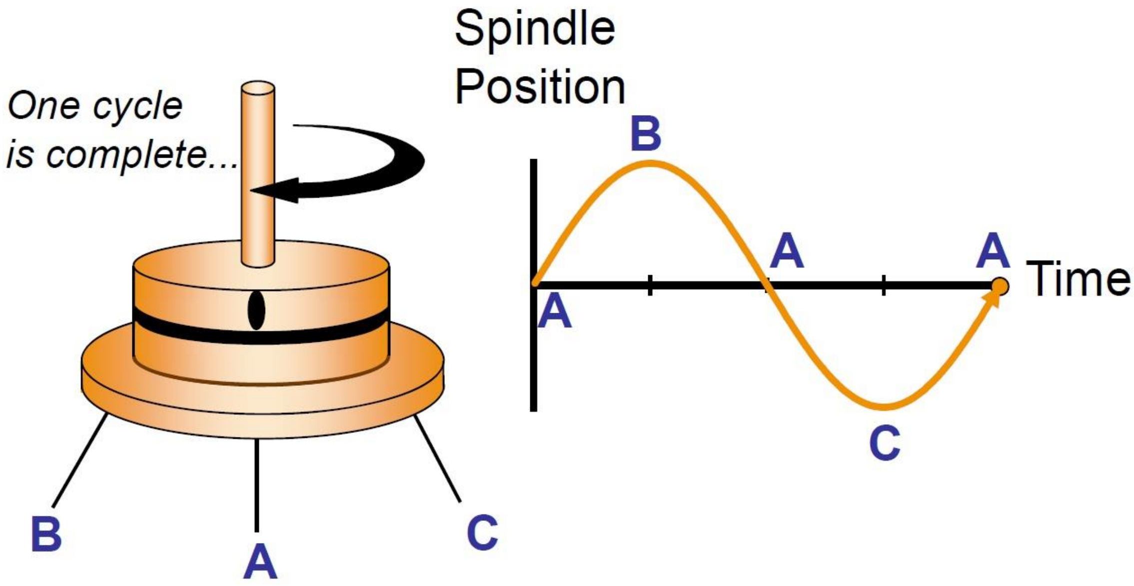


Figure 4.3: Illustration of working mechanism in MSCRT

5. The strain was registered every 10 seconds for the creep cycle.
6. Non-recoverable creep compliance (J_{nr}) was calculated mathematically, which can be computed by dividing by applied shear stress:

$$\text{Non} - \text{recoverable Creep Compliance (Jnr)} = \frac{\text{Unrecovered Shear Strain}}{\text{Applied Shear Stress}} \quad (4.3)$$

7. The following formula was also used to determine % recovery after one second, which took nine seconds:

$$\text{Recovery (\%)} = \left(\frac{\text{Peak Strain} - \text{Unrecovered Strain}}{\text{Peak Strain}}\right) * 100 \quad (4.4)$$

To simplify the above relations and descriptive parts of the calculations, the following graph (Figure 4.4) illustrates the recovered and non-recovered parts of the strain curve for one cycle, which could be repeated for other cycles but with diversity in the strain values.

8. The detailed procedure can be found in Appendix C.1, in which each sample of binder for each of the three temperatures underwent the same process.

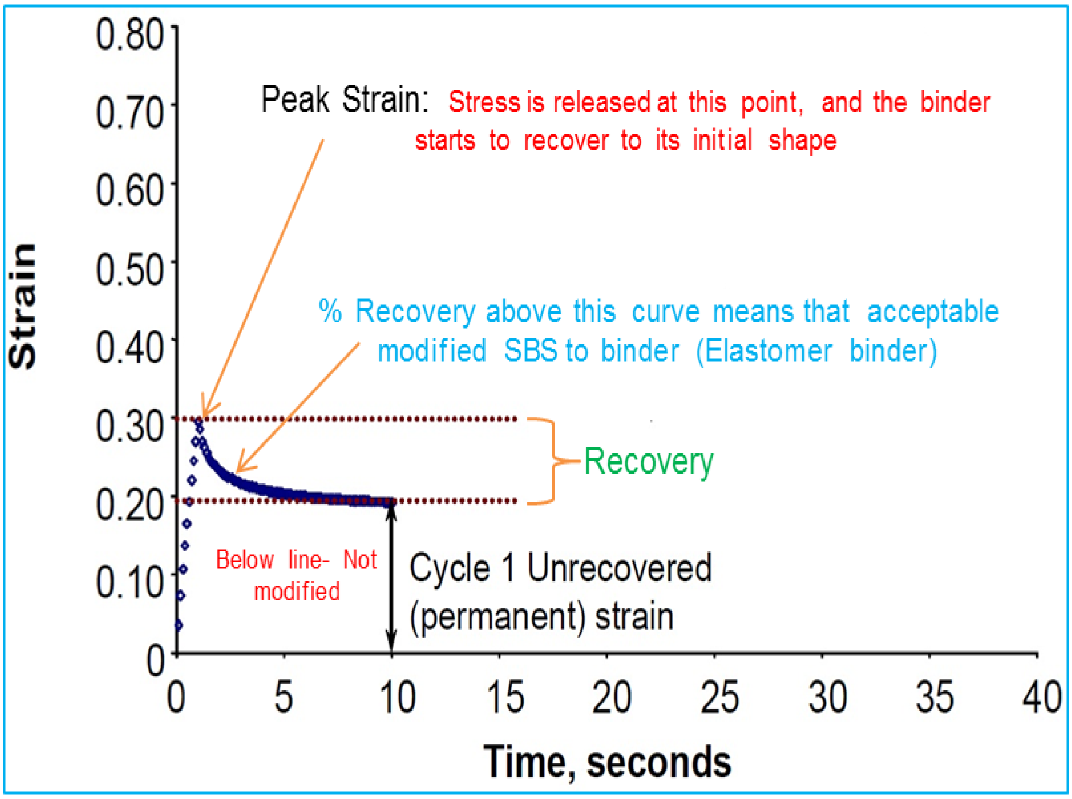


Figure 4.4: Illustration of recovered and unrecovered parts in MSCRT

4.3 Wheel Tracking Test (WTT)

This test typically measures the rut depth generated by repeated passage of a wheel tracker over prepared asphalt mixture slabs. The laboratory simulation of the rutting phenomenon must reasonably approach real flexible pavement stress conditions in the field. For this test, a mix of European and British standard has been used; wheel tracking equipment, specially developed to European standard with the British standard (BS 598-110:1998) parameters (see test parameters), was standardized to carry out the test.

Since the rutting mechanisms occur in hot environmental circumstances, this test obviously provides a good indication of rutting susceptibility of the prepared slab in the real world. This test should also reflect the main rutting mechanisms described in the literature review (Section 2.2.1), in which the generated shape associated by the deformed slab with the known rut depths should indicate whether it is the result of densification mechanism or shear plastic deformation (analyzed and discussed in detail in chapter five, Section 5.3).

In order to replicate the practical importance associated with realistic and reliable conditions in mix design applications, British standard parameters (BS 598-110:1998) were devised for this test, despite the limitation of insufficiency, in terms of applying wheel load and the test duration, which is only 45 minutes. In other words, if the test duration were longer, relatively more deformations could be achieved, as the European standard wheel tracking test extends to 10,000 cycles. Nevertheless, different percentages of SBS polymer were utilized and the diversity in the outcomes can be a considerably appropriate indication for investigating permanent deformation.

4.3.1 The Main Parameters

Test temperature in this study was set at 60°C in order to replicate real traffic conditions. The other reason for choosing this particular temperature was that polymer performs better in high temperatures. The test lasted 945 cycles (45 minutes) or rut depth 15 mm (whichever was sooner), with 520±5 N of load estimated by BS 598-110:1998, applied by a solid wheel through the lever arm, while the main measurement was mm/cycle or mm at which one cycle equals two passes, backward and forward.

4.3.2 The Main Procedure

1. The fabricated slabs with dimensions 305mmx305mmx60mm (Section 3.2.5) were placed on new moulds and underwent a conditioning process at 60°C in storage from the day before, to be ready for the test.
2. Wheel tracker cabinet was set at the same temperature using the software designed for this test.
3. The samples were fixed in turn (SBS-modifier based slabs with the three percentages and conventional slabs) under the wheel on a fixed plate and the temperature monitor of the sample was set inside a hole previously generated on the slab (temperature monitoring hole) to fix the thermometer.
4. The wheel load connected with the applied weight on the lever arm (Figure 4.5) was placed on the middle of the slab.
5. The linear variable differential transformers (LVDT) designed to measure the rut depth were accurately fixed and then calibrated on the slab to be ready for testing.

6. The wheel tracker gate was closed to gain the desired temperature before running the test via the software.
7. Vertical displacement was measured at intervals of one minute or less, allowing the progress of the rut to be explored.
8. Each slab was subjected to the same procedure. The detailed procedure can be found in Appendix C.2.

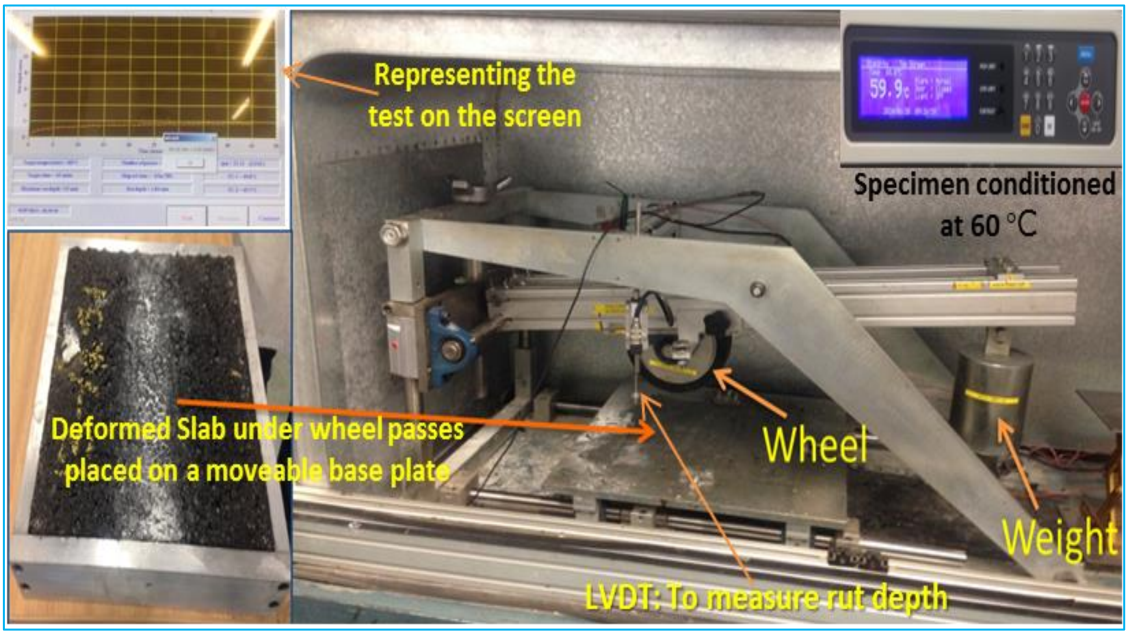


Figure 4.5: Wheel tracking test configuration

4.4 Nottingham Asphalt Tester (NAT)

Essentially, the NAT is a set of tests, which can be modelled and configured in order to carry out indirect tensile mode testing for bituminous mixture specimens. These tests could include ITSMT, RLAT, ITFT, etc. In other words, the NAT set of tests allows diametral testing (ITSMT and ITFT), as well as uni-axial testing (RLAT) configurations. Since this project explores permanent deformation, the first two tests were considered to be undertaken as they can be correlated with this subject.

4.4.1 Indirect Tensile Stiffness Modulus Test (ITSMT)

The ITSMT for mixture specimens is defined in accordance with BS EN 12697-26:2004. A pulsating load is applied centrally between the upper and lower platens and the resultant peak transient deformation along the horizontal diameter is measured. Usually, cylindrical specimens are cored from the slabs manufactured for WTT in the laboratory. The applied load transfers vertically across the diameter of the cylindrical specimen, leading to generation of a horizontal deformation, which is measured by the two LVDTs. The two LVDTs are mounted diametrically on each side in a rigid frame clamped to the test specimen. Since ITSMT is considered to be a less destructive test, it is usually undertaken prior to the RLAT test, which is considered to be more destructive for specimens. Thus, the determination of resilient modulus, the total horizontal deformation, can be obtained.

This test was performed for bituminous mixture specimens of 100mm diameter and 50mm height. For each percentage of SBS-modified specimens, four samples were tested, while five samples were tested for the conventional specimens. Fundamentally, prior to the test, the specimens underwent a conditioning process during the day before, until the time of testing. Most importantly, the specimen thicknesses were measured at four different positions, whereas the specimen diameters were measured at six positions. Consequently, the mean values of the measured thicknesses and diameters were determined for input in the software.

4.4.1.1 The Main Parameters

The ITSMT was performed for the bituminous mixture samples at 20^{O}C. It is important to control the test temperature, because inherently, temperature can have an effective contribution, which can change the stiffness. More specifically, 1^{o}C of temperature can have a 10% effect on stiffness modulus, which is considerably high. Therefore, it must be critically taken into consideration before and during testing due to its sensitivity to temperature. Furthermore, for this study, the test 40/60 penetration grade bitumen was used. The diameter of cylindrical samples was 100 mm while the sample thicknesses were limited to 40±4mm. The mean horizontal deformation was 5±2 μm, which was 5 microns, with Poisson's ratio of 0.35 with target rise time 124 m.secs. Finally, the ITSMT was carried out in two orthogonal orientations.

To determine the stiffness modulus, the following equation was used:

$$S_m = \frac{L(v+0.27)}{D*t} \tag{4.5}$$

Where:

S_m: Stiffness modulus of asphalt mixtures (MPa)

v: Poisson's ratio,

t: Mean thickness of the specimen (mm)

L: The peak value of applied load (N)

D: The peak horizontal deformation (mm).

4.4.1.2 The Main Procedure

In accordance with BS EN 12697-26:2004 the test underwent the following procedure:

1. The specimens underwent a conditioning process prior to the test at 20^{O}C from the day before the test (stored overnight), as well as during the test inside the cabinet.
2. The mean values of the measured dimensions as illustrated in Appendix C.3 (diameter and thickness in mm), the main testing requirements and parameters were inputted to the software for each sample.
3. After a cylindrical specimen was fixed between the upper and lower loading platens, the test machine was calibrated for the software to obtain control and start the test by accurately moving the front and back LVDTs.
4. The test was started for the first diameter in the first five pulses after the preliminary pulses. Then the sample was set on the second diameter by orientating the specimen 90^0 followed by checking the LVDTs and starting the test for the second diameter.
5. Measured and adjusted stiffness modulus (MPa) was recorded for each specimen.
6. Each sample was subjected to the same procedure.

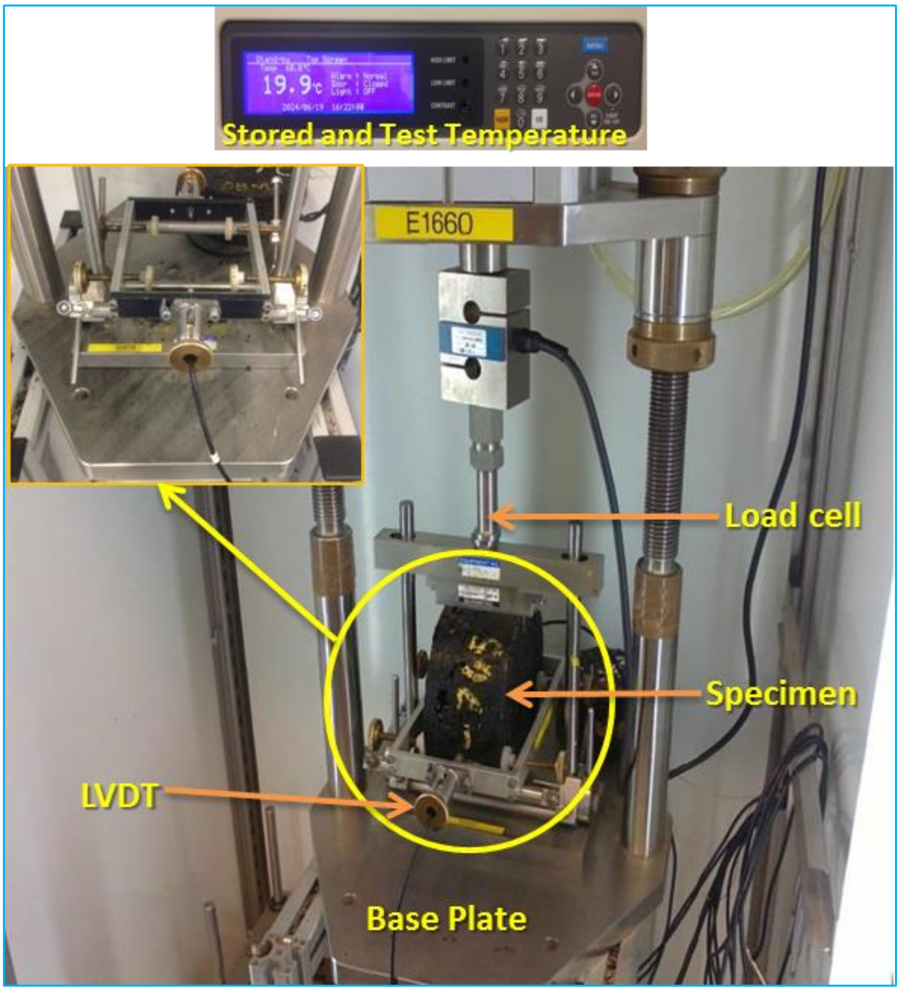


Figure 4.6: ITSMT configuration using NAT apparatus

4.4.2 Repeated Load Axial Test (RLAT)

As with all NAT based tests, the RLAT is performed using cylindrical specimens with a diameter of 100mm and thickness 40mm according to DD 226:1996. In the test, the specimen was positioned vertically between the upper and lower loading platens. This is designed to be relatively wider in order to hold a specimen. The repeated load was axially applied, so the vertical deformation of the specimen could be recorded by two LVDTs mounted on the upper loading platen. Unlike with the ITSMT (described above), RLAT tends to be a more destructive test due to a larger number of pulses applied throughout the test, which generate axial strain on the cylindrical specimens.

Fortunately, this test can provide a reasonable appropriation of real traffic circumstances in terms of repeated loading. Specifically, the mechanism of the test is designed to apply a one second loading followed by one second rest extending from 1,800 to 3,600 pulses. The resting time offers a chance for the specimen to recover; if there is a tendency to recover, it is correlated with the elasticity performance of the mixtures. Despite the inherent condition of the test, which tends to represent the real world in terms of actual traffic conditions, it was better to carry out this test at a temperature of 40^{O}C rather than 30^{O}C. Obviously, this temperature is considered to be much more realistic, particularly for rutting indication.

4.4.2.1 The Main Parameters

There are several fundamental parameters for RLAT. Testing temperature is between 30^{O}C and 40^{O}C. A standard test utilizes a vertical stress of 100 kPa at 30^{o}C for 1,800 pulses, although it can be extended up to 3,600 pulses to attain a relatively more realistic outcome. As a conditioning stage, the test is first initiated with a stress of 10 kPa for 10 minutes to ensure that the working mechanism is completely acceptable (including loading platens). The designed pulsating load provides a square wave form with a frequency of 0.5 Hz, in which one second pulse duration is followed by a rest of one second.

4.4.2.2 The Main Procedure

The test was undertaken in accordance with BS DD 226:1996 using the same samples in the ITSMT: five conventional specimens plus SBS-modified specimens (four samples of each percentage of polymers), with the following procedure:

1. Test specimens underwent a resting (unloading) process after ITSMT followed by conditioning prior to the test, at a temperature of 30^{O}C throughout the day prior to the test.
2. Since the same specimens were used as in ITSMT, the same dimensions and thicknesses were inputted to the software.
3. All other parameters were also inputted and a temperature of 30^{O}C was set inside the cabinet. Meanwhile, the number of pulses was set (1,800).
4. Each specimen was positioned and fixed on the frame under the load cell.
5. The two LVDTs were calibrated until accepted by the software (normally red flash appears on the screen).

6. The test was started and the outcome appeared on the screen, representing axial strain deformation with respect to the number of pulses. Moreover, the deformation was monitored by the LVDTs mounted on the upper loading plate. The permanent axial deformation was recorded after every specific load application until the test was completely performed. The detailed procedure can be found in Appendix C.4

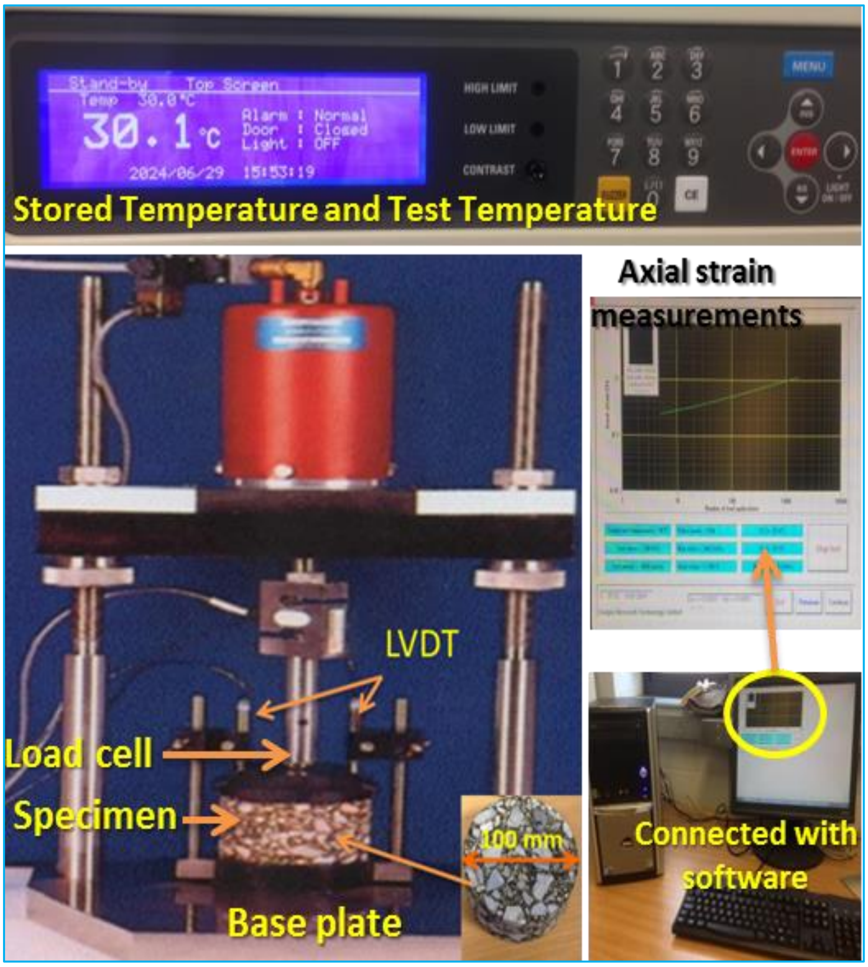


Figure 4.7: RLAT configuration using NAT apparatus

4.5 Summary of the Key Points

In summary of the experimental programme and testing methods explained above, a significant number of key points have arisen. The most fundamental point to emerge can be quoted as a question: 'Why were these tests carried out exclusively?' This deserves the following outlined clarifications to provide a fully understandable conclusion that may provide the answer.

- **MSCRT** is a test which has received a lot of attention and significant acceptance by pavement authorities. It allows the discovery of a much more economic usage of polymers to improve rutting resistance in binders, despite its applicability being time consuming. It is also considered to be the most accurate test for the prediction of rutting susceptibility, which has strongly correlated parameters, i.e. J_{nr} and %R.
- **WTT** is also intended to simulate field conditions as closely as possible, while being able to perform under a temperature of 60 ^{0}C, at which rutting is more likely to occur.
- **ITSMT** can also be better correlated with pavement rutting because it is so sensitive to temperature and loading time; these are rather similar conditions under which permanent deformation occurs.
- **RLAT** also reflects the slow movement of traffic, which leads to the most deformation in real roadways as it gives a chance for recovery. Furthermore, testing parameters are reliable for rutting such as strain rate, representing the steady state condition, which is a direct measurement of the non-recoverable strain; therefore it is directly related to permanent deformation (viscous strain).
- Interestingly, extensive data sets can be obtained in order to compare the obtained results and provide coefficient correlations between the different tests.

CHAPTER FIVE: EXPERIMENTAL RESULTS AND DISCUSSIONS

5.0 Overview

This chapter provides a critical analysis and discussion of the most significant results obtained, followed by reasonable further interpretations for the arguable points. Firstly, the results from each of the four tests are discussed in detail with necessary interpretations. Secondly, taken together, the main correlations between the tests are discussed and a review of the main findings is also summarized. Returning to the hypothesis and the key questions posed at the beginning of this study, it is now possible to investigate the experimental outcomes in order to fulfil the fundamental aims and objectives of this research. The tests carried out for the binder, including diverse PMB and different modifier based mixtures, may enhance the current findings to be added to a growing body of literature on permanent deformation. Furthermore, the main correlation between the four tests is also discussed.

5.1 Foil Method Results

The main methodology of foil method was mentioned in the previous chapter (Section 4.1.5); it is important here to highlight the most significant results to ensure whether or to what extent the measured air void content is close to the proposed air void for the designed mixtures. As four different mixtures were prepared for this project (one conventional and three modified mixtures), the determination of the air void content has been obtained as an average per mixture.

As Table 5.1 shows, there is slightly small difference in air void content between the different mixtures. It is apparent from this table that very little of the air void content from the conventional mixture is close to the 7% of SBS-modified mixture, whereas the larger diversity is between 3% and 5% of the SBS-modified mixtures. Likewise, from this data, it can be seen that the mixture modified with 5% resulted in the lowest value of air void. What is interesting in this data is that the designed air void content (5%) is reasonably close as the obtained air void (approximately 5%), which may reveal acceptable mixtures.

Table 5.1: Determination of air void contents for the different mixtures

Relative density of foil (Mg/m^3)	Bulk density sealed (Mg/m^3)	Max. density of mixture (measured) (Mg/m^3)	Air void content of mixture (%V_m)	SBS Content (%)	Average air void content (%)
14-1384	2.417	2.586	6.529	Conventional	5.80%
14-1385	2.434	2.586	5.878		
14-1386	2.404	2.586	7.028		
14-1387	2.447	2.586	5.386		
14-1388	2.471	2.586	4.443		
14-1389	2.442	2.586	5.561		
14-1390	2.484	2.586	3.943	3% of SBS	6.56%
14-1391	2.440	2.586	5.647		
14-1392	2.385	2.586	7.783		
14-1393	2.356	2.586	8.884		
14-1394	2.501	2.586	3.288	5% of SBS	4.88%
14-1395	2.439	2.586	5.673		
14-1396	2.466	2.586	4.626		
14-1397	2.432	2.586	5.937		
14-1398	2.413	2.586	6.706	7% of SBS	5.37%
14-1399	2.476	2.586	4.242		
14-1400	2.464	2.586	4.717		
14-1401	2.436	2.586	5.819		

The single most striking observation to emerge from the data comparison (Figure 5.1) is that the diversity in SBS contents in the mixtures did not have a significant variation to the air void contents. Two discrete reasons emerged from the small differences. First, coring the slabs to create the cylindrical specimens may have slightly affected compressibility on the samples. Second, the compaction level may possibly not have been sufficient at the edges of the slabs as mentioned in the limitations (Section 1.3).

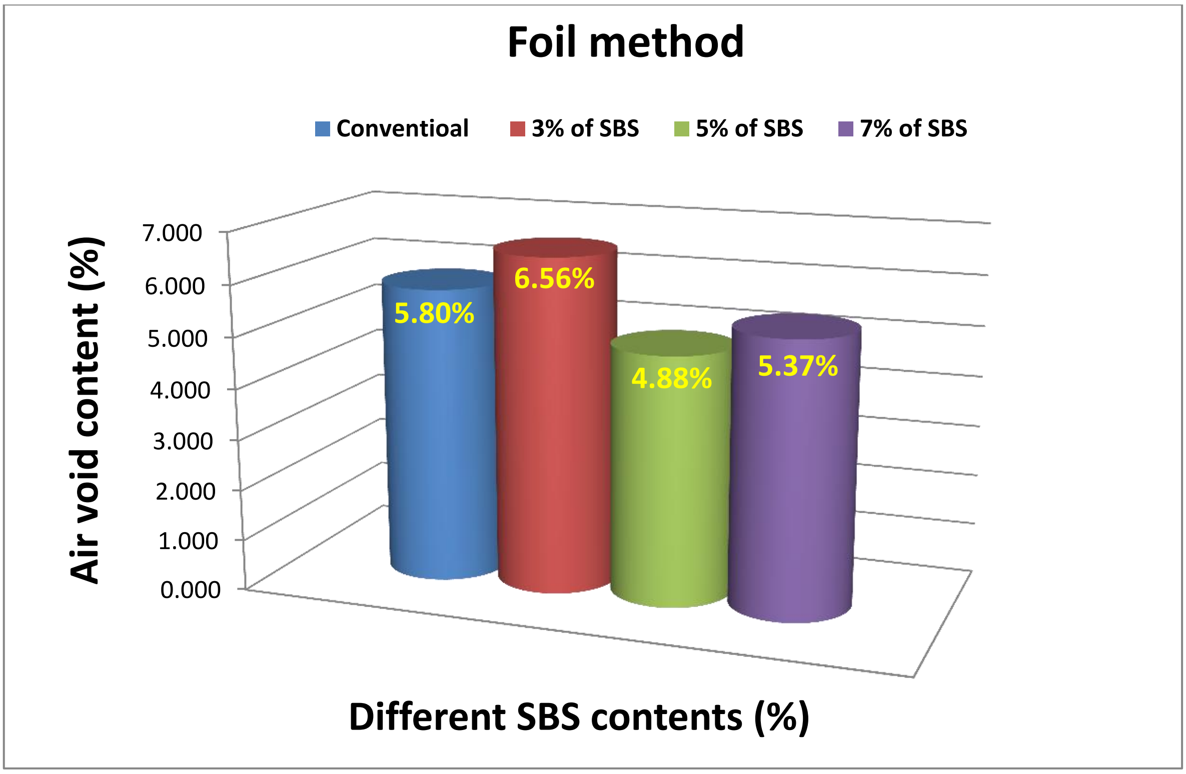


Figure 5.1: Illustration of air void contents of different SBS-modified asphalt mixtures

5.2 Multiple Stress Creep Recovery Test (MSCRT) Results

The DSR was introduced as a tool to carry out the MSCRT for both of the original (unaged) binders and PMBs, including different percentages to assess the permanent deformation susceptibility of these binders at three different temperatures per sample prior to use of the same binder source to undertake the mixture tests. The results represented in Figures 5.2 to 5.5 illustrate the intercorrelations among the different levels of performance of pin binders and SBS-modified binders, in which the obtained non-recoverable compliance from pin binders are much higher than the PMBs in all temperatures. Furthermore, it seems that the J_{nr} values in PMBs tend to decrease favourably with increasing polymer contents in all temperatures. This confirms the significant role of polymer in improving the elasticity behaviour illustrated in the literature review (Section 2.5). It can be noted that the PMBs with 5% and 7% content performed reasonably well in all the temperatures, with the priority for 7% SBS. Taken together, these results indicate that the optimum percentage of SBS appears to be 7% with the exception at 60°C (Figure 5.3), at which 5% of PMB provides greater performance. After repeating the test in this particular temperature, the J_{nr} value resulted in a slightly less value in favour of 7% of SBS, which indicates a better elastic performance, although it was in competition with the 5% at the beginning before the stress levels increased, after which the differences appeared more clearly (Figure 5.5).

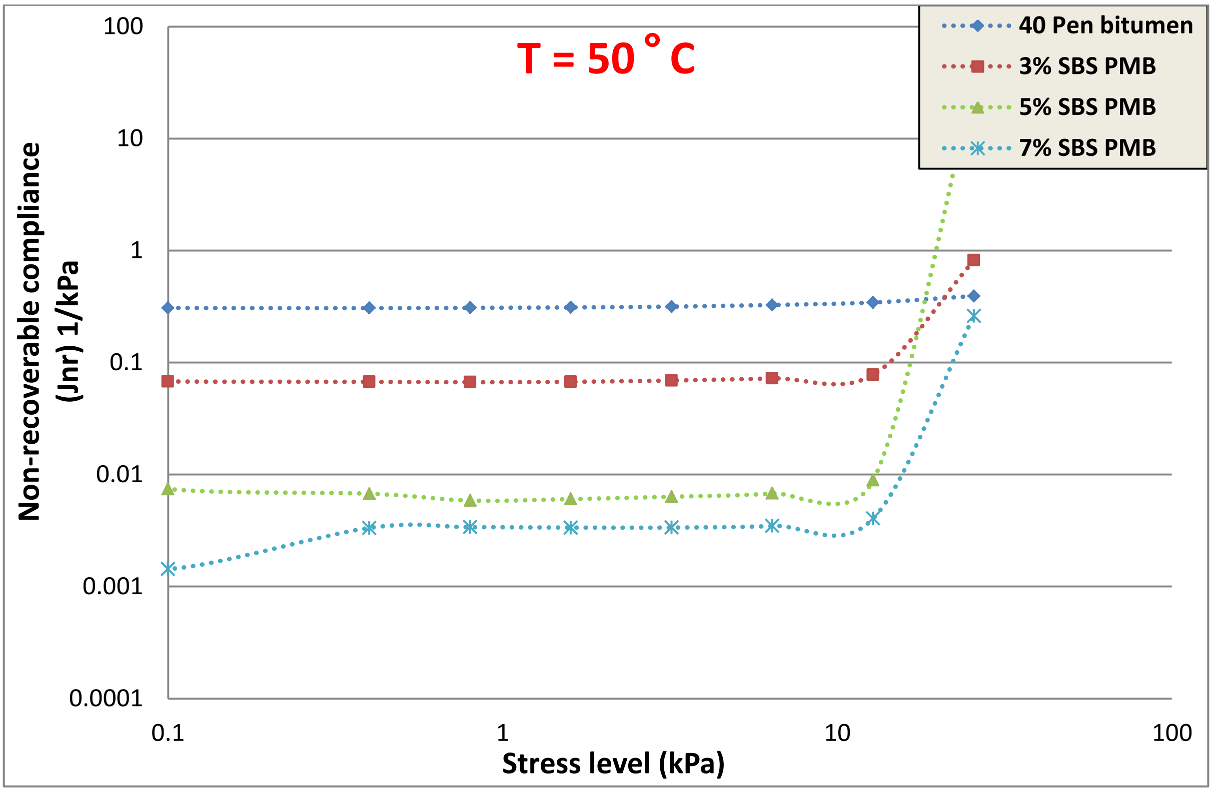


Figure 5.2: Relationship between non-recoverable compliance and stress levels at 50°C

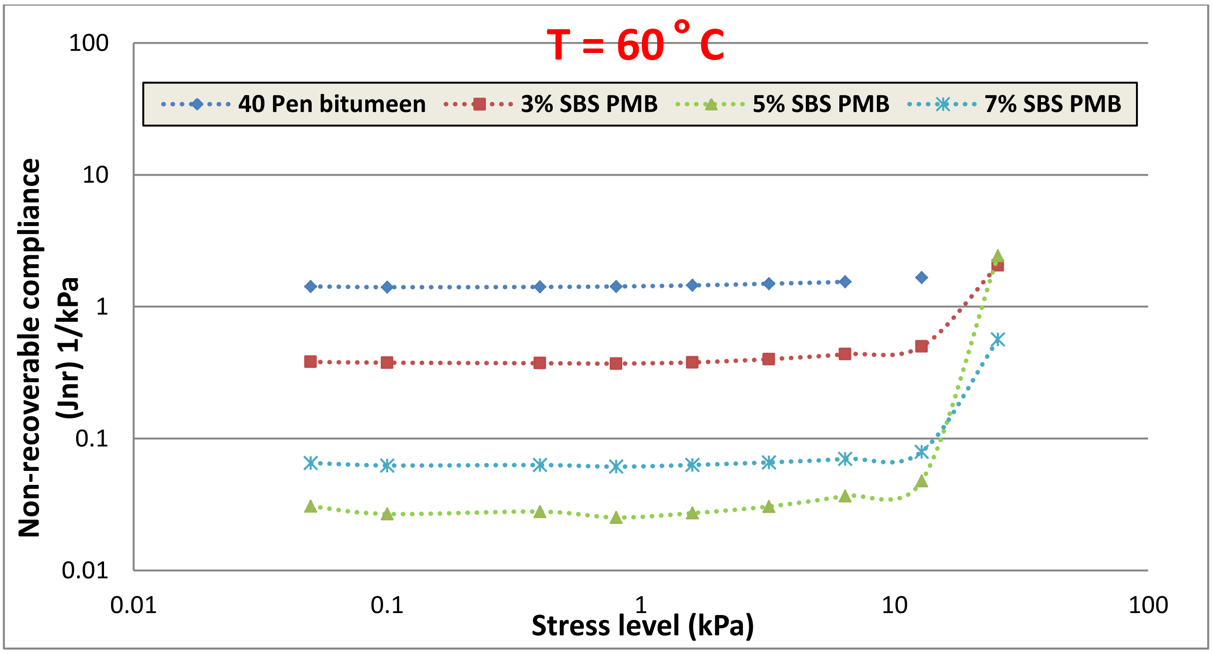


Figure 5.3: Non-recoverable compliance versus stress levels at 60°C

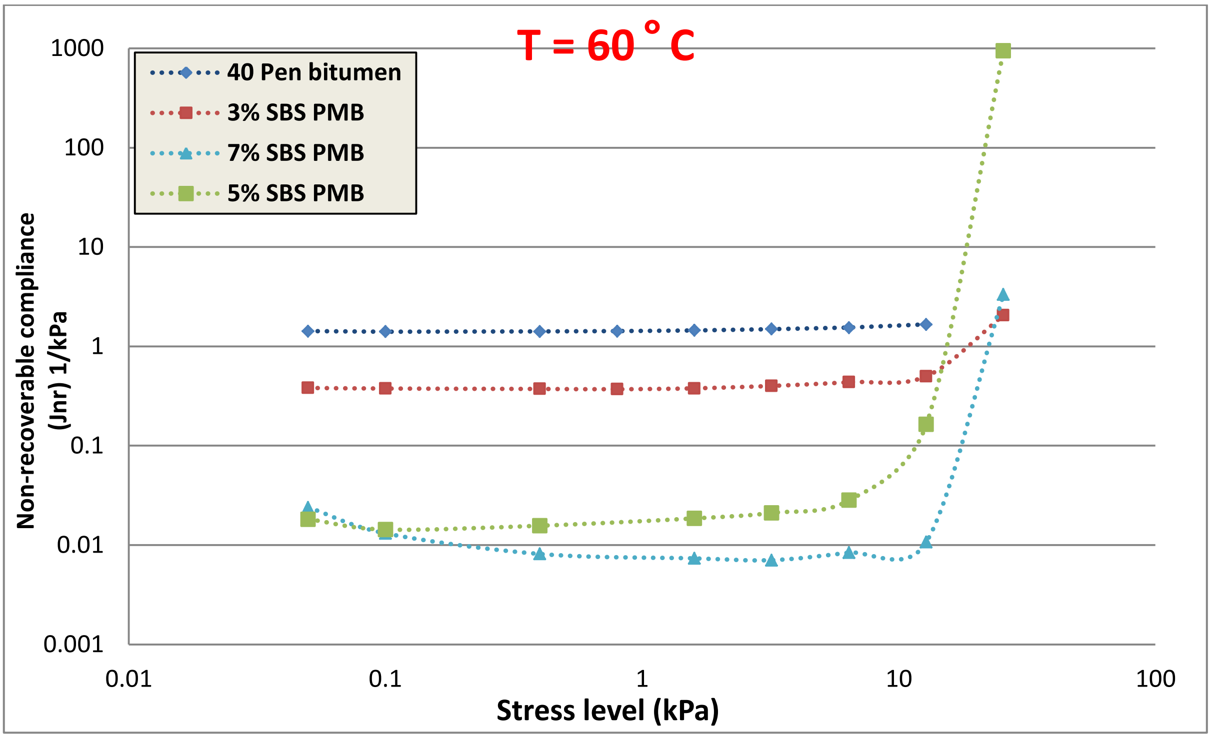


Figure 5.4: Non-recoverable compliance versus stress levels at 60°C (when the test was repeated)

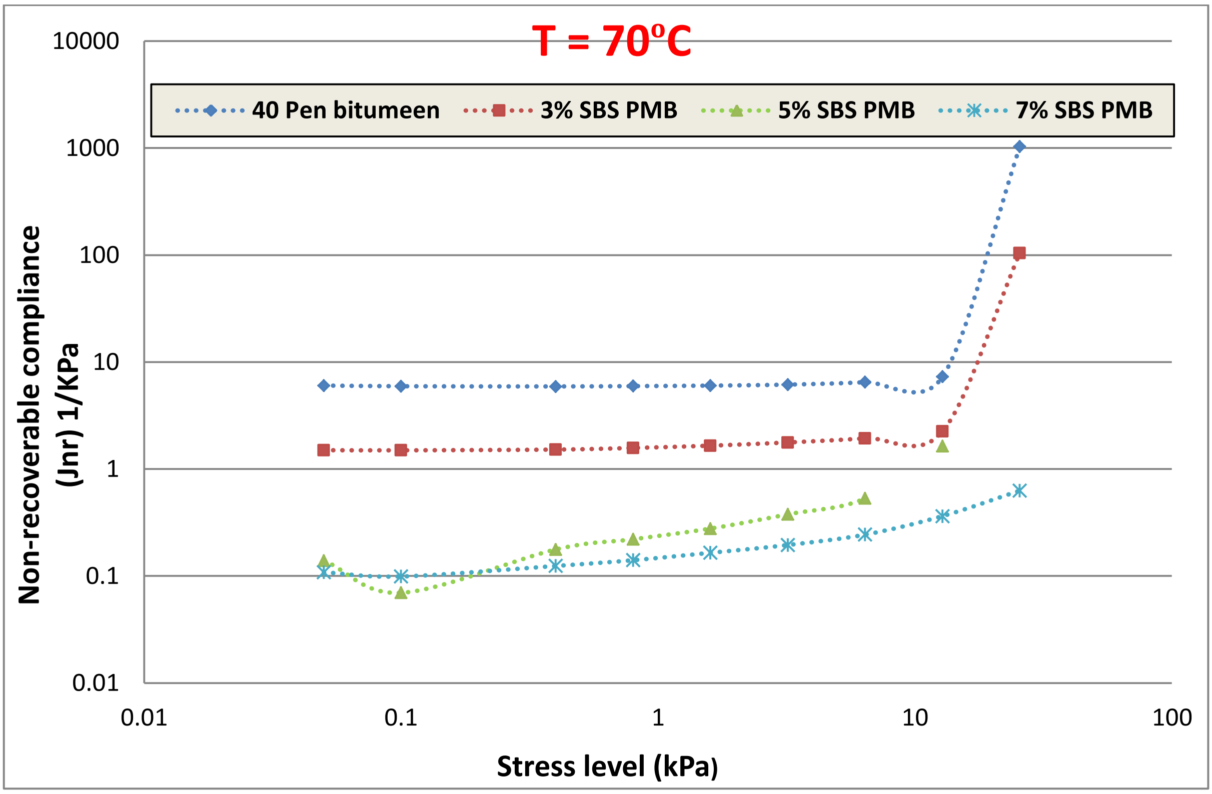


Figure 5.5: Non-recoverable compliance versus stress levels at 70°C

Unlike with the non-recoverable compliance (discussed above), recovery parameter (%R) represents the ability of binder to recover. Figures 5.6 to 5.9 show that the recovery tendency of pin bitumen is quite poor, at about 5% as an average for all temperatures, which reaches zero percentage at 70°C, while the PMBs tend to recover at different percentages. Apart from 3% SBS that seems not to recover favourably, both other SBS-modified binders (5% and 7%) performed considerably well (approximately 90% as an average); their recovery behaviours are rather close to each other with a slightly small lead for the 7% at all the temperatures, except at 60°C; that provided the most striking result to emerge, in which the 5% mix obtained a much higher recovery than its counterpart, before repeating the test. This may be due to non-homogeneity of the binder during the blending process, as also confirmed by previous studies (Airey 2003; Golalipour 2011 and Tatic 2006).

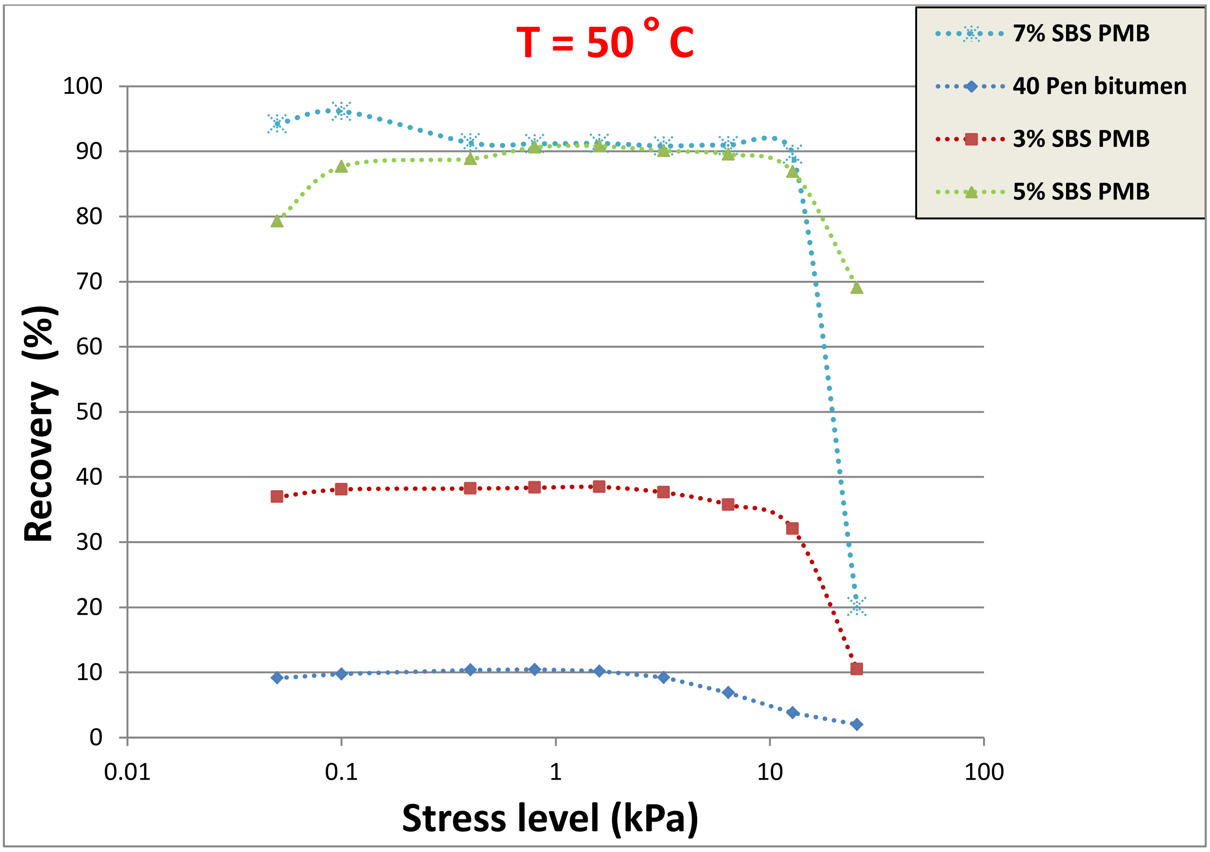


Figure 5.6: Relationship between recovery and stress levels at 50°C

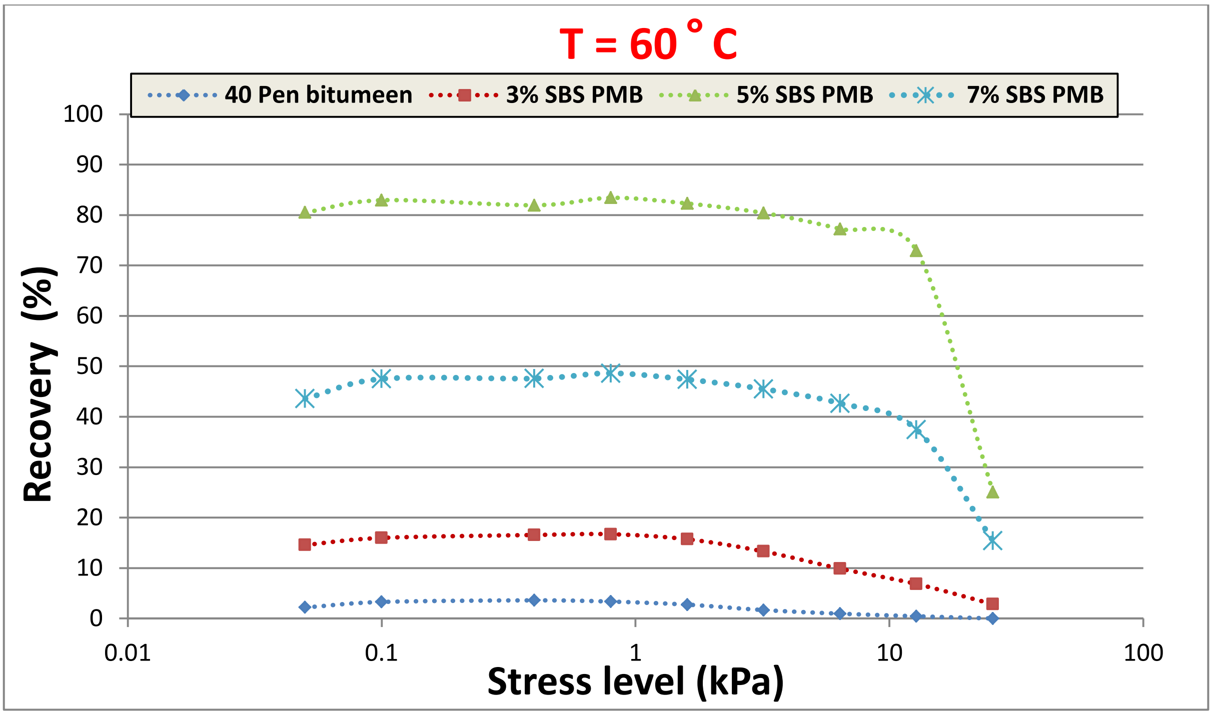


Figure 5.7: Recovery versus stress levels at 60°C

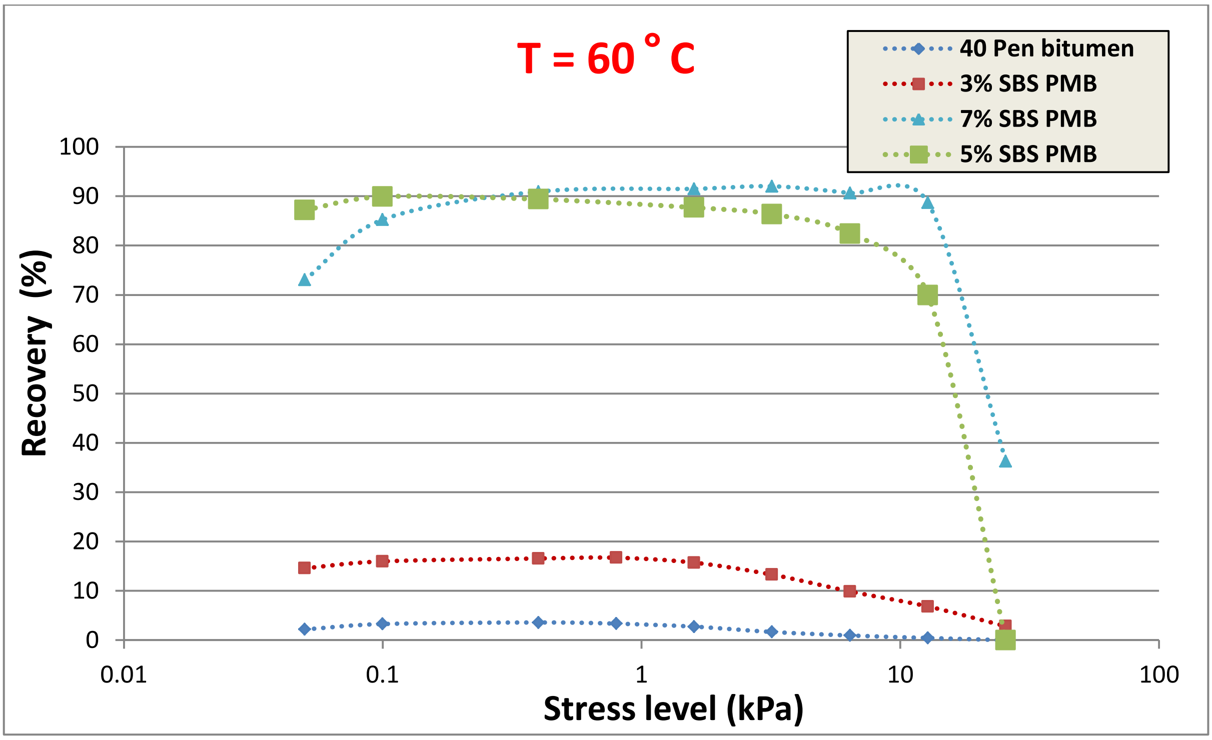


Figure 5.8: Recovery versus stress levels at 60°C (after repeating the test)

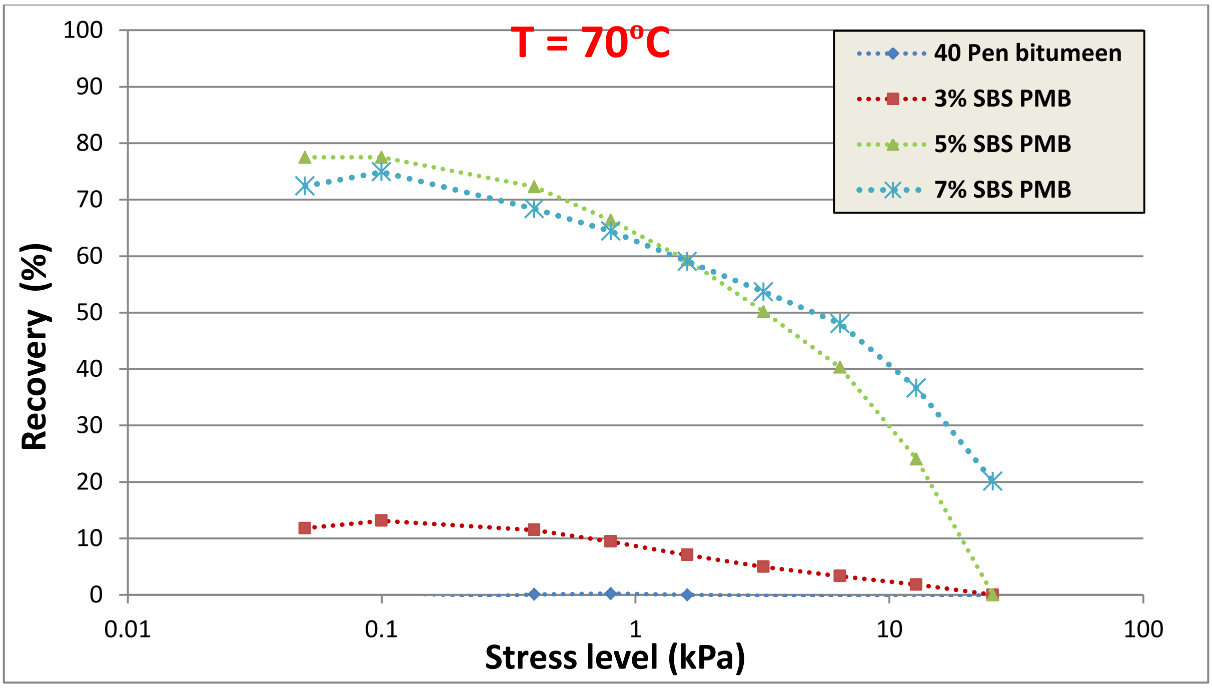


Figure 5.9: Recovery versus stress levels at 70°C

In line with the above interpretations, these findings further support the importance of the relation between plastic response of binder to rutting performance, at which by increasing temperature and stress levels, rutting resistance tends to reduce (illustrating a less plastic response - mentioned in sections 2.31 and 2.3.2); also, the recovery percentages appear to decrease as the applied stress levels and the temperatures increase. This appears more clearly at a temperature of 70°C. The bar charts in Figures 5.10 to 5.13 further clarify this relation; by releasing the stress level and temperatures, the binders begin a poorer recovery, tending toward the lowest percentages despite possibly more appropriate performances of 5% and 7% of PMBs with various fluctuations. This has previously been confirmed by Golalipour (2011), who explained that adding 10 kPa stress can increase the binder's nonlinearity and susceptibility to stress levels; meanwhile, it can also demonstrate a clearer image of the PMB's permanent deformation resistance.

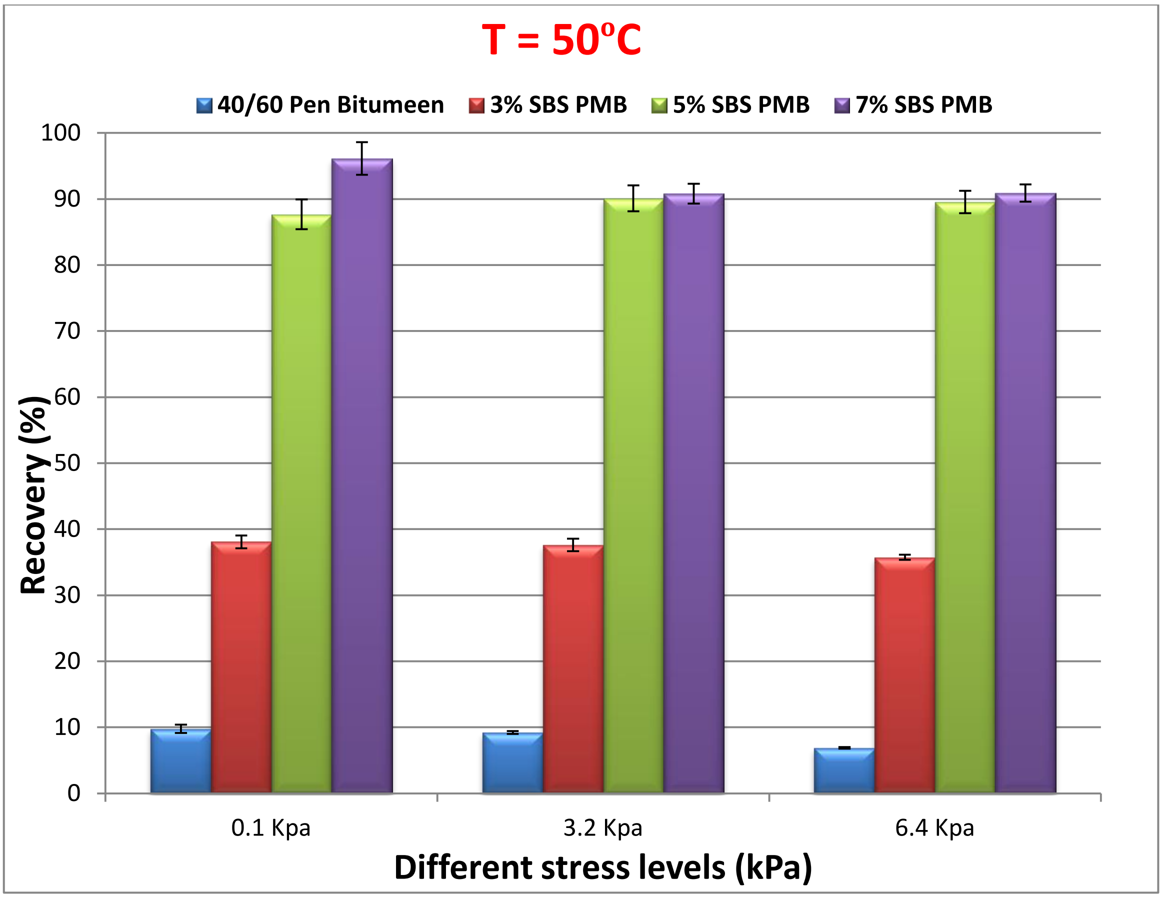


Figure 5.10: Relationship between recovery and different stress levels at 50°C

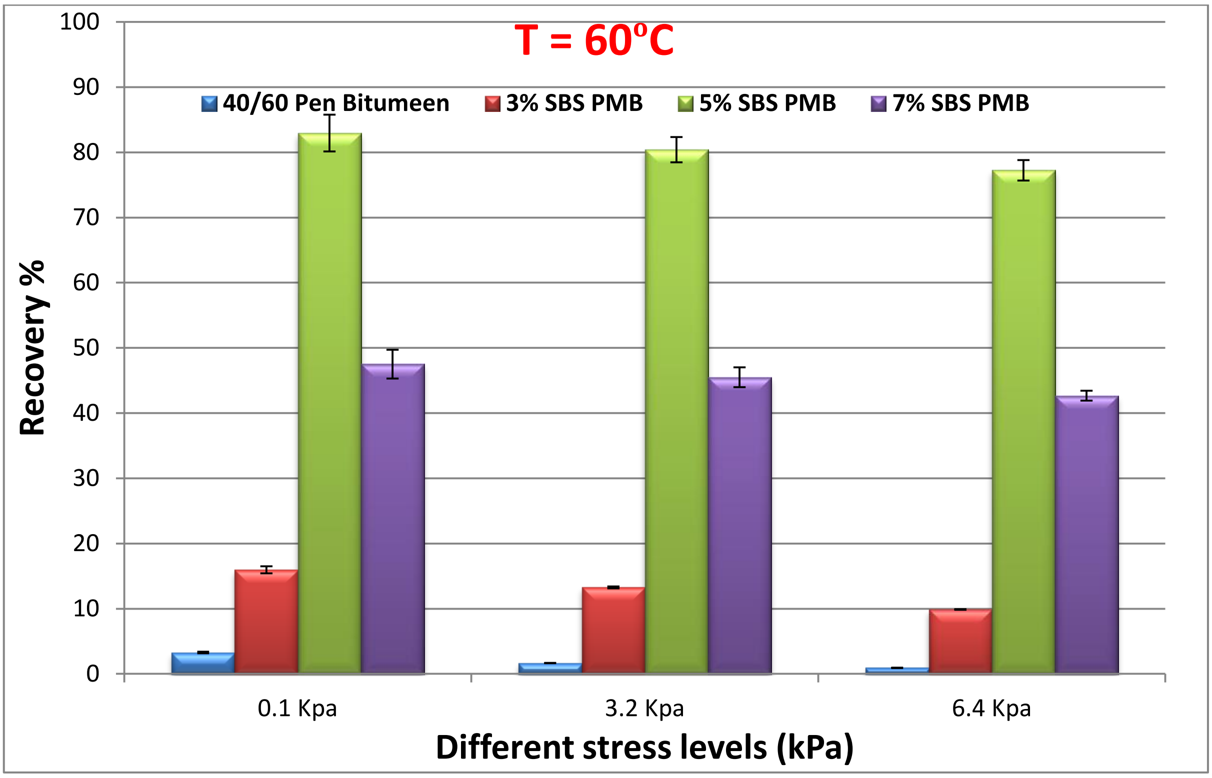


Figure 5.11: Recovery versus different stress levels at 60°C

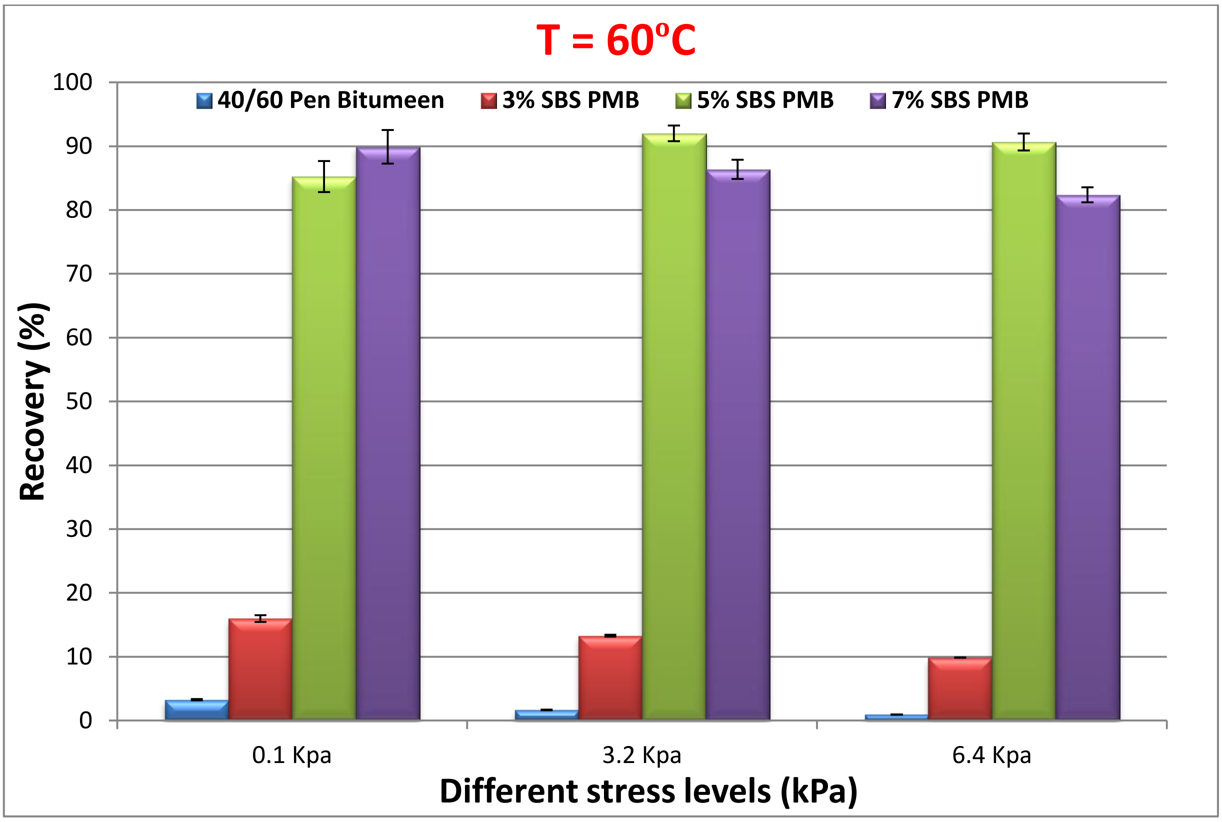


Figure 5.12: Recovery versus different stress levels at 60°C (after repeating)

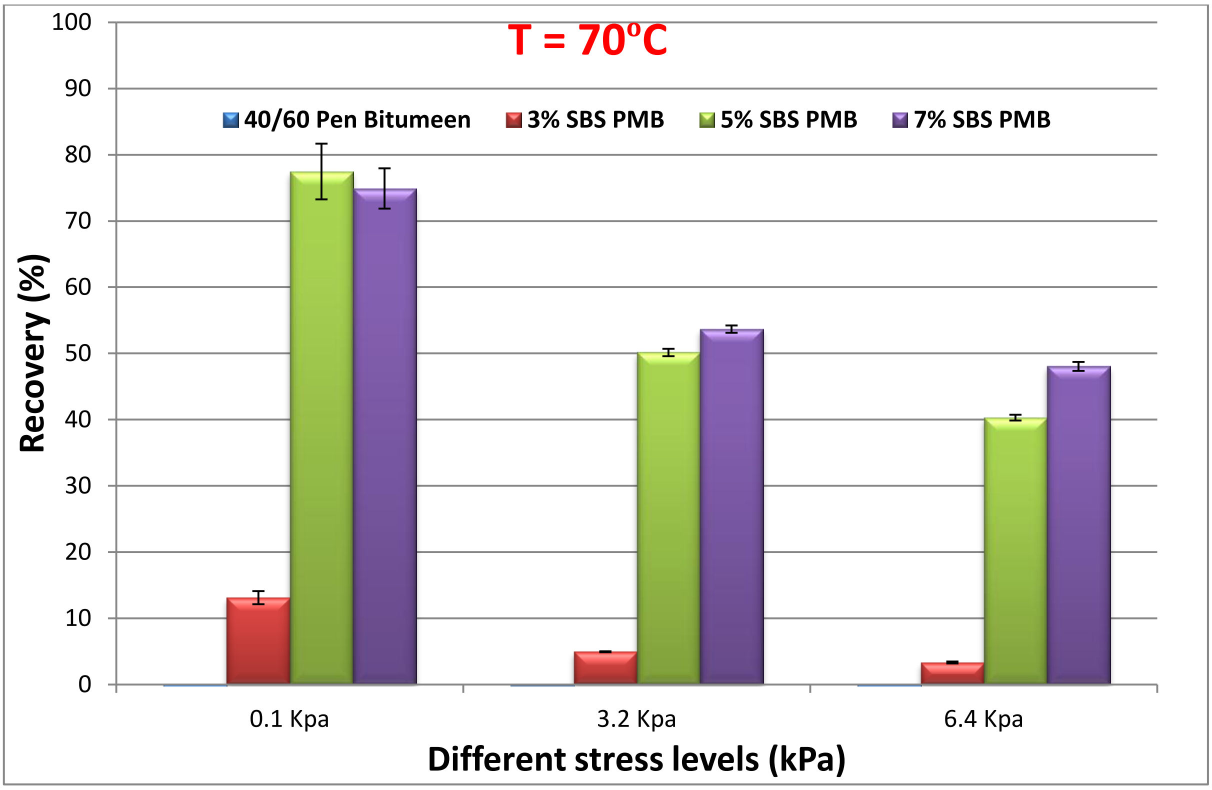


Figure 5.13: Recovery versus different stress levels at 70°C

Owing to the importance of elasticity behaviour, AASHTO produced a graph called the AASHTO curve to show elastic response of the binders. Figures 5.14 to 5.21 show that the 5% and 7% SBS-modified binders located above the line indicate a valid polymer modification that allows a reasonably suitable recovery throughout the different stress levels (including 3.2kPa stress separately) and testing temperatures, whereas the 3% PMBs and base binders tend not to recover properly, which are located under the elastic response line. The relation between percentage recovery and non-recoverable compliance in the figures demonstrate better elasticity for 5% and 7% PMBs; it appears that both of the percentages are close in terms of elasticity, apart from the first test at 60°C. To establish whether or how the AASHTO curve relates to the curve for rutting, no further explanation can be highlighted except that the points located below the line identify the failure to recover of the non-modified binder with an elastomeric polymer; conversely the points located above the line indicate that the binder is modified within an acceptable limit of elastomeric polymer and passes to recovery. Contrary to expectations, this has not been explained further, even by previous studies regarding the AASHTO curve despite of its great importance.

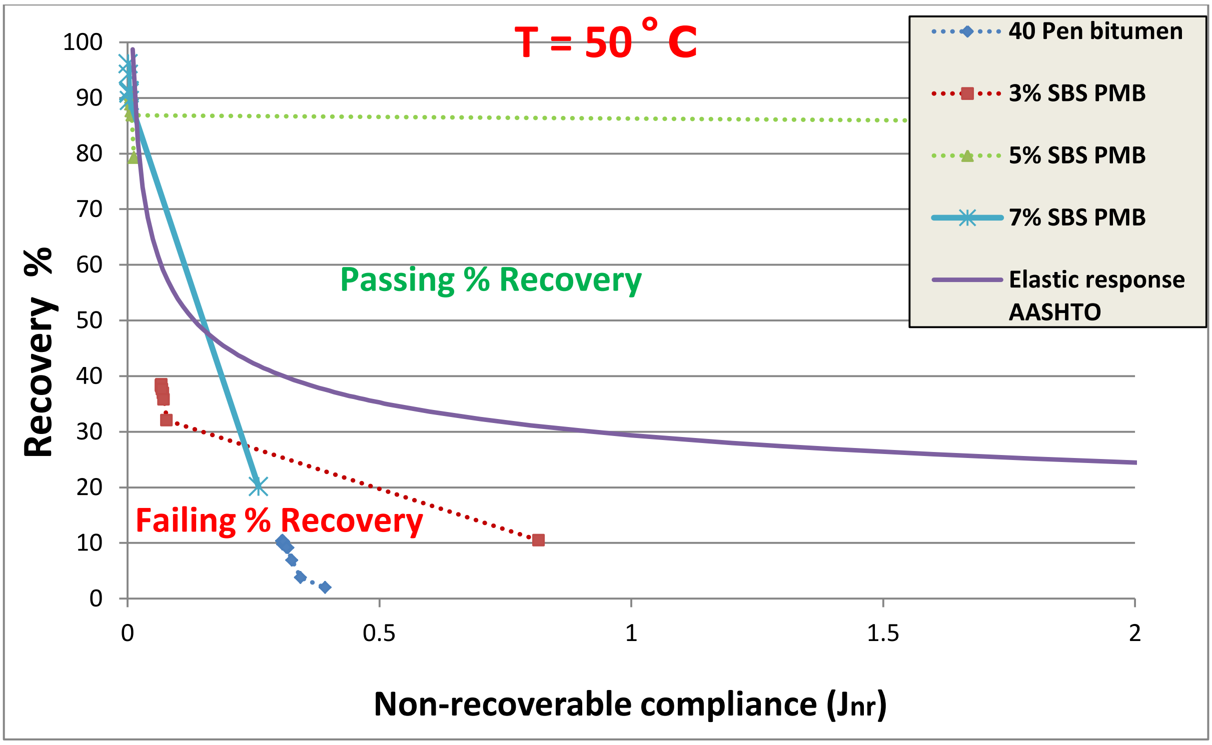


Figure 5.14: Recovery versus non-recoverable using AASHTO curve at 50°C

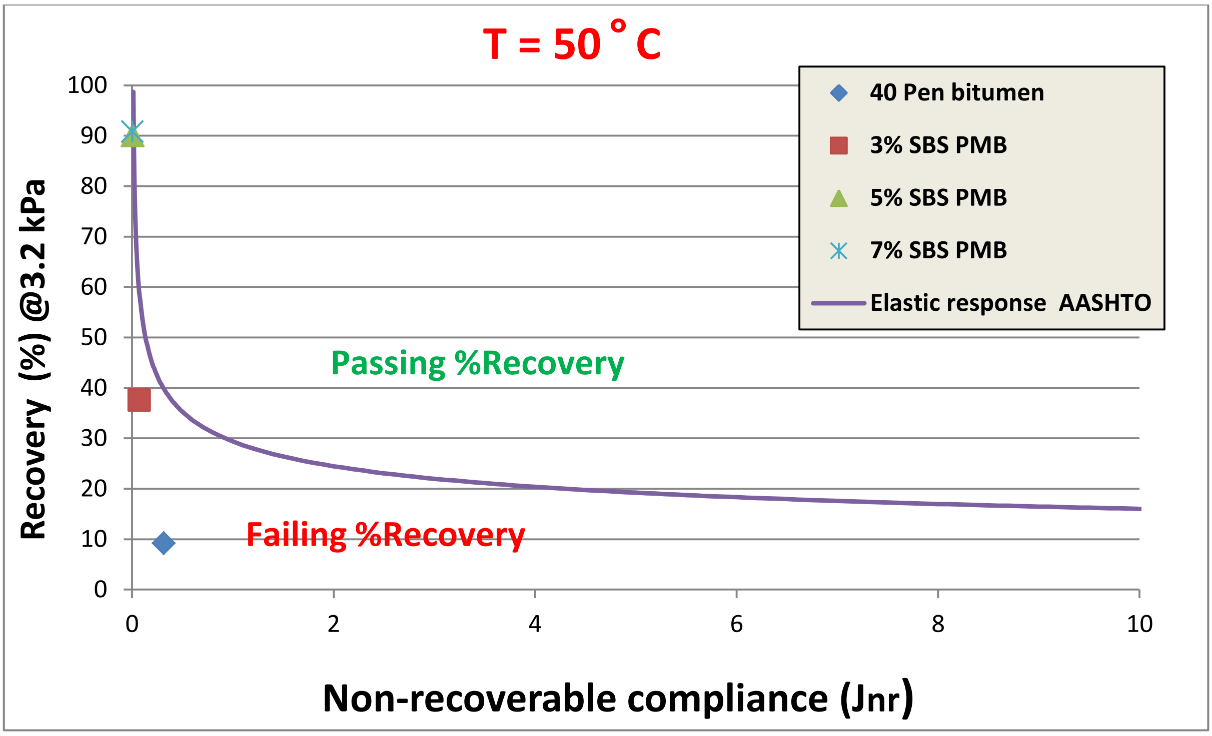


Figure 5.15: Recovery in 3.2kPa stress versus non-recoverable using AASHTO curve at 50°C

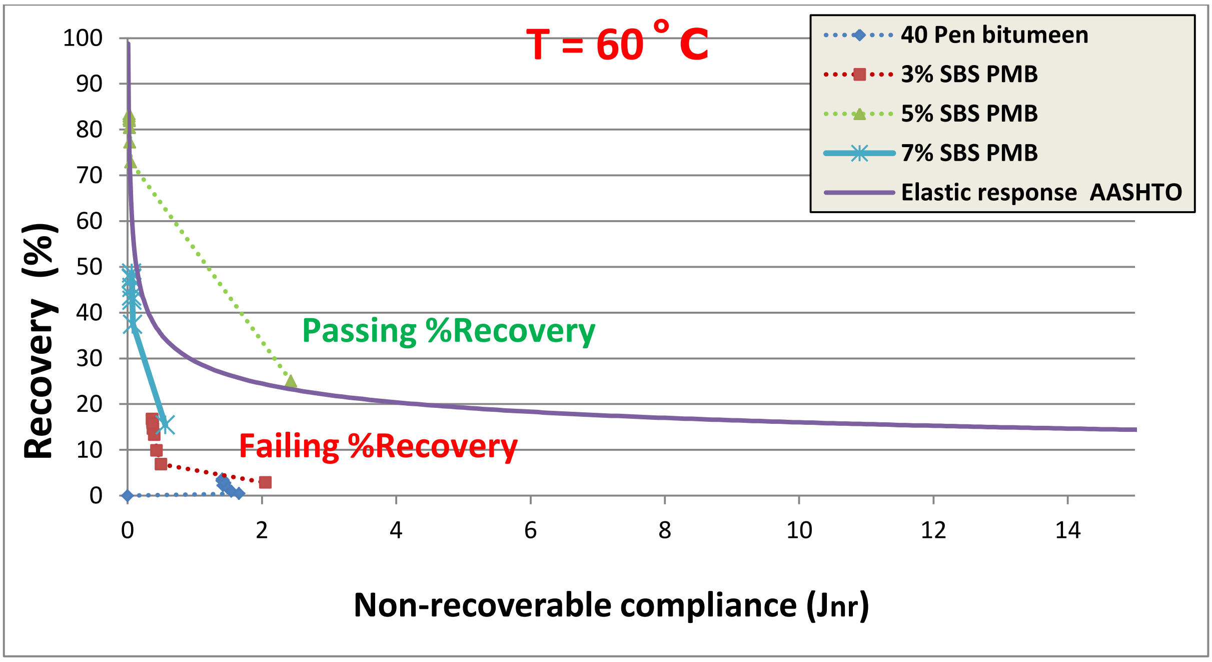


Figure 5.16: Recovery versus non-recoverable using AASHTO curve at 60°C

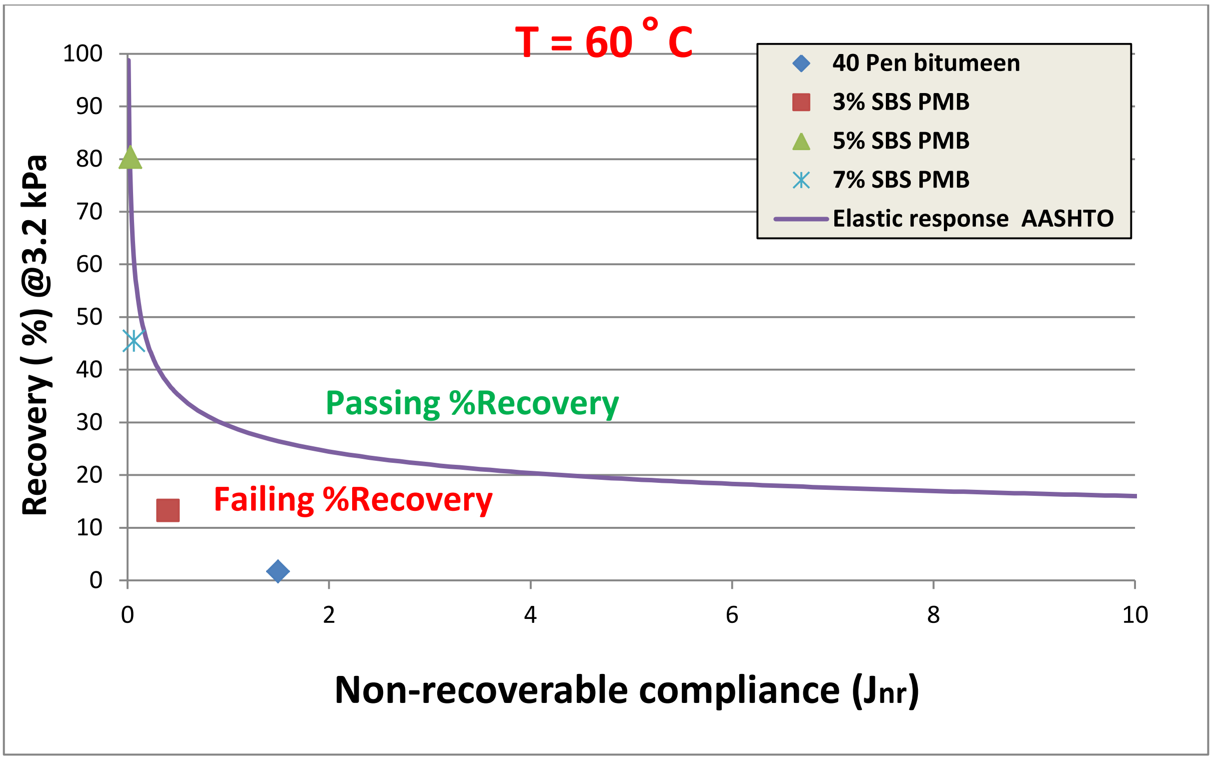


Figure 5.17: Recovery in 3.2kPa stress versus non-recoverable using AASHTO curve at 60°C

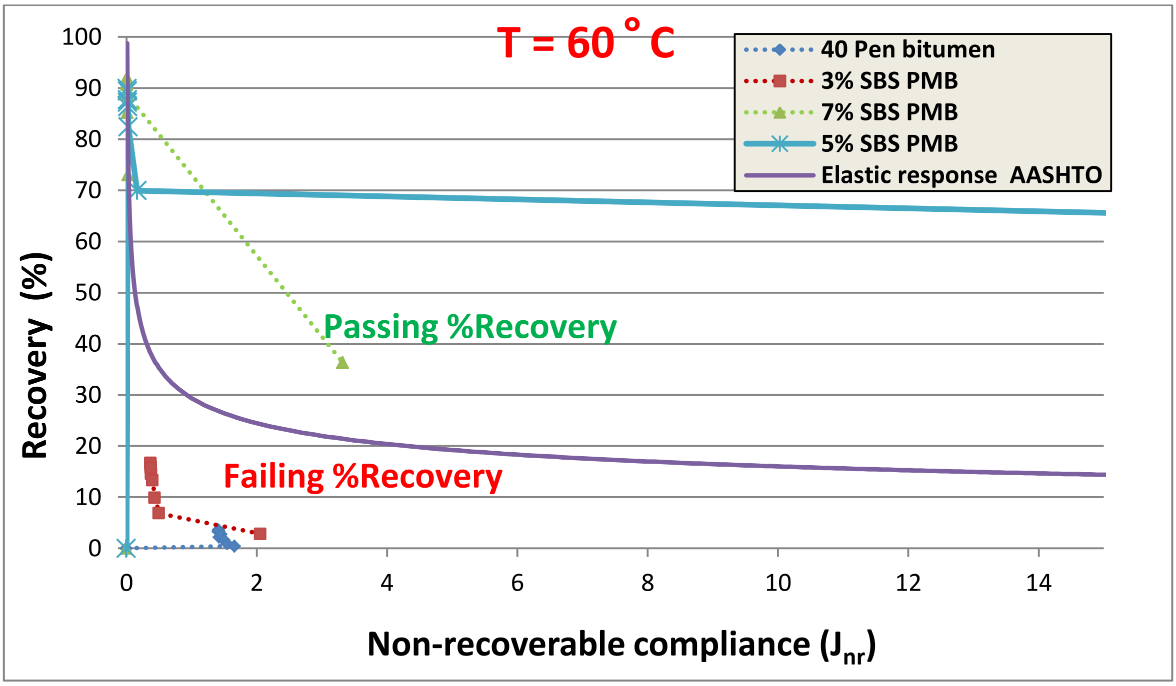


Figure 5.18: Recovery versus non-recoverable using AASHTO curve at 60°C (after repeating the test)

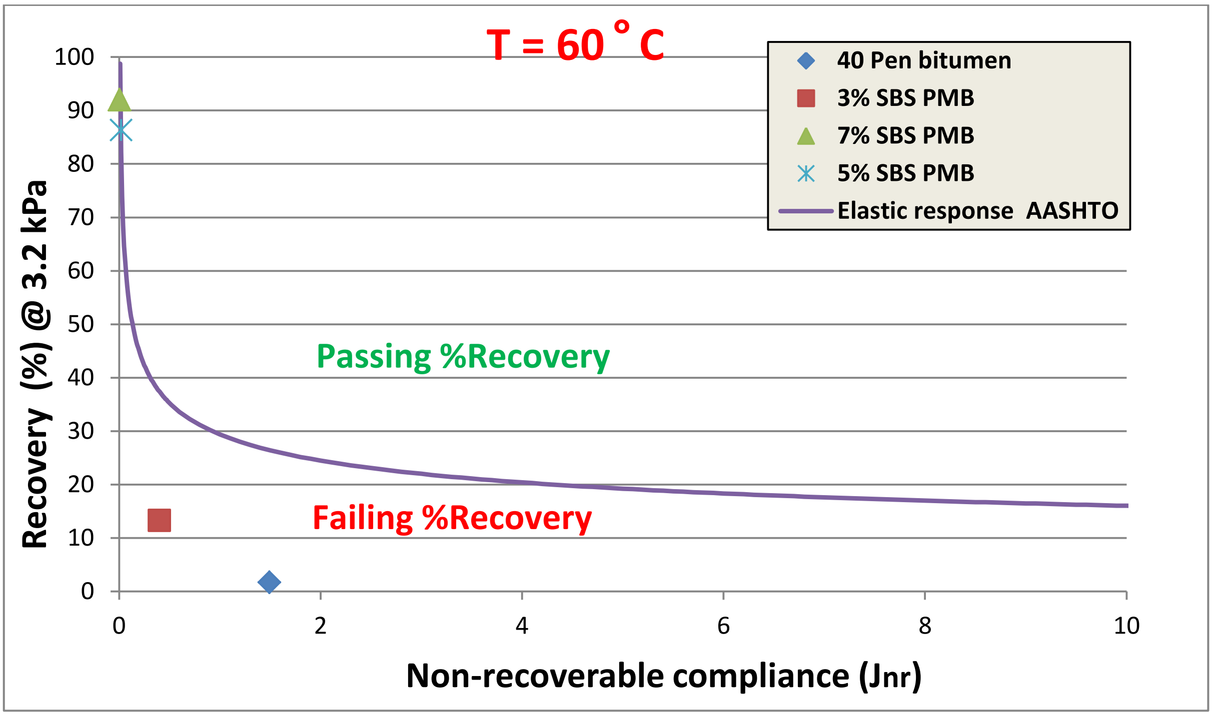


Figure 5.19: Recovery versus non-recoverable using AASHTO curve at 60°C (after repeating the test)

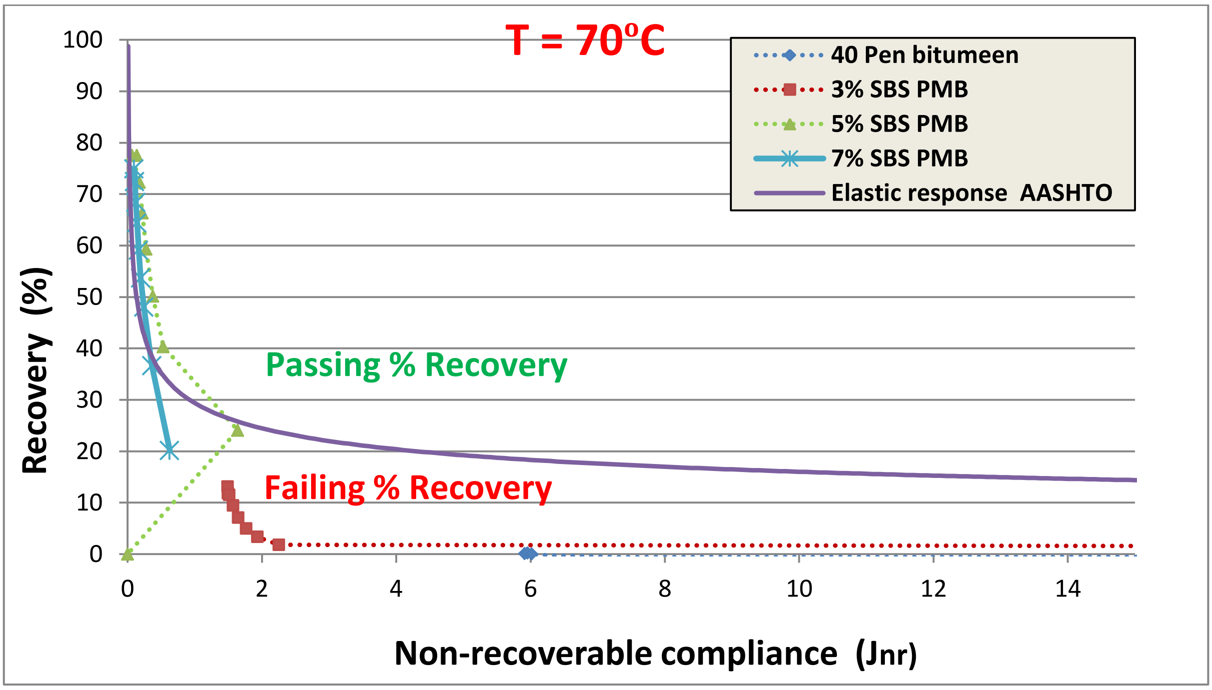


Figure 5.20: Recovery versus non-recoverable using AASHTO curve at 70°C

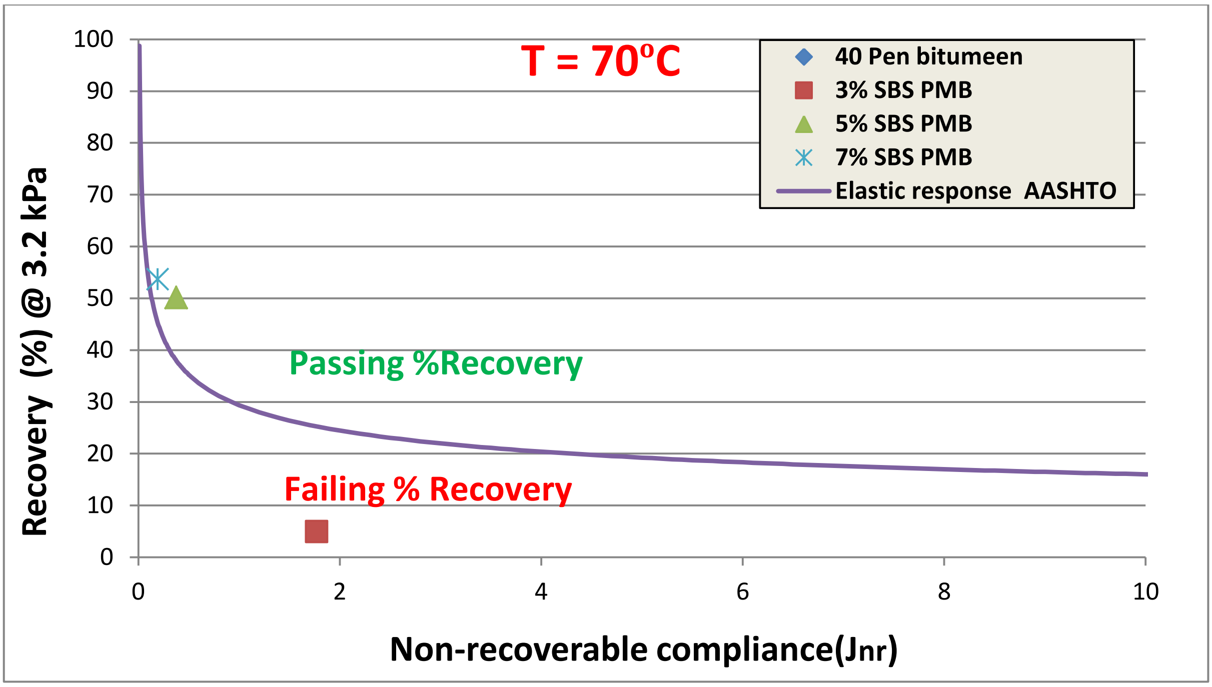


Figure 5.21: Recovery in 3.2kPa stress versus non-recoverable using AASHTO curve at 70°C

In order to identify for further clarification a more precise estimation of assessing the behaviour of the different binders, a relation between accumulated strain and accumulated time was drawn in Figures 5.22 to 5.26. On a larger scale, unlike the rest of the figures, the first two graphs (Figures 5.22 and 5.23) start from 250 seconds and finish at 600 seconds to illustrate the strain line behaviour more clearly. It is obvious from the graphs that the pen binder shows larger strain, which generates poorer resistance to permanent accumulated strain, followed by 3% of PMBs at all the temperatures. Likewise, the PMBs, namely at 5% and 7%, represent acceptable performances that are rather close to each other with a small lead for 7% SBS, which performs better but only a little better, except during the first test at 60°C (Figure 5.24), in which the 5% SBS performed with better resistance to strain before repeating the test at the same temperature again. Although the difference is so small between the two aforementioned percentages, it is more likely that the 5% SBS is a more preferable and economic percentage of added polymer, although 7% tends to perform with slightly better resistance to permanent strain, specifically at high temperatures (Figures 5.25 and 5.26). The 7% SBS seems to be significantly survivable under accumulated strain. There is also a jump in data from 5% SBS, particularly at 600 and 700 seconds respectively for both figures, which is either related to the violent stresses in causing instrumental errors.

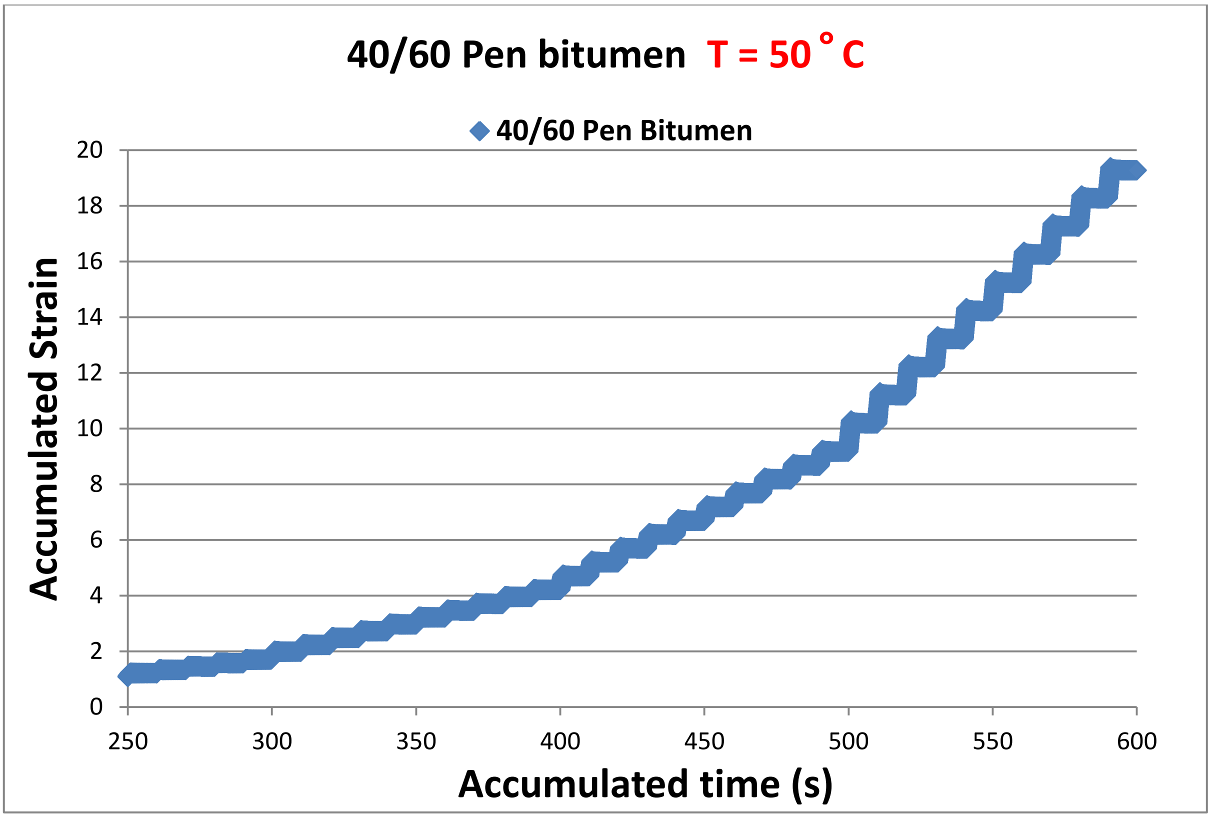


Figure 5.22: MSCRT response curve for pen bitumen at 50°C

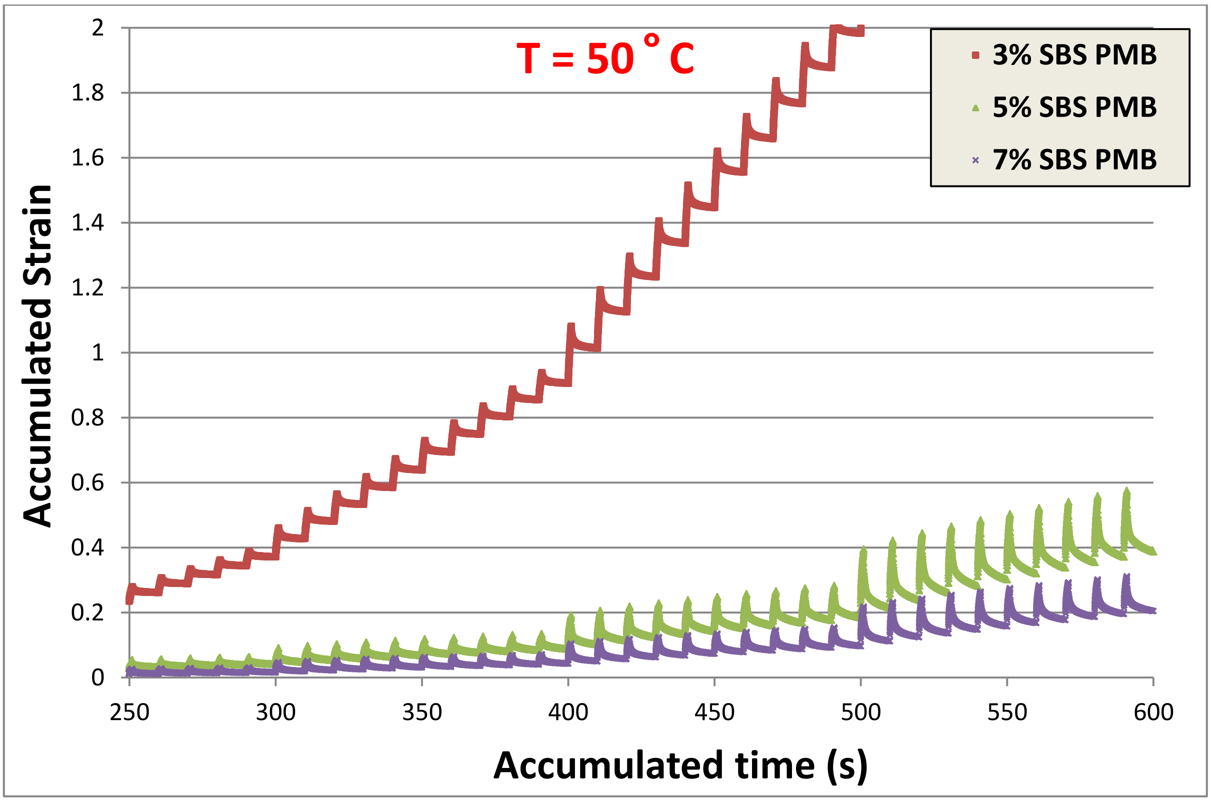


Figure 5.23: MSCRT response curve for PMBs at 50°C

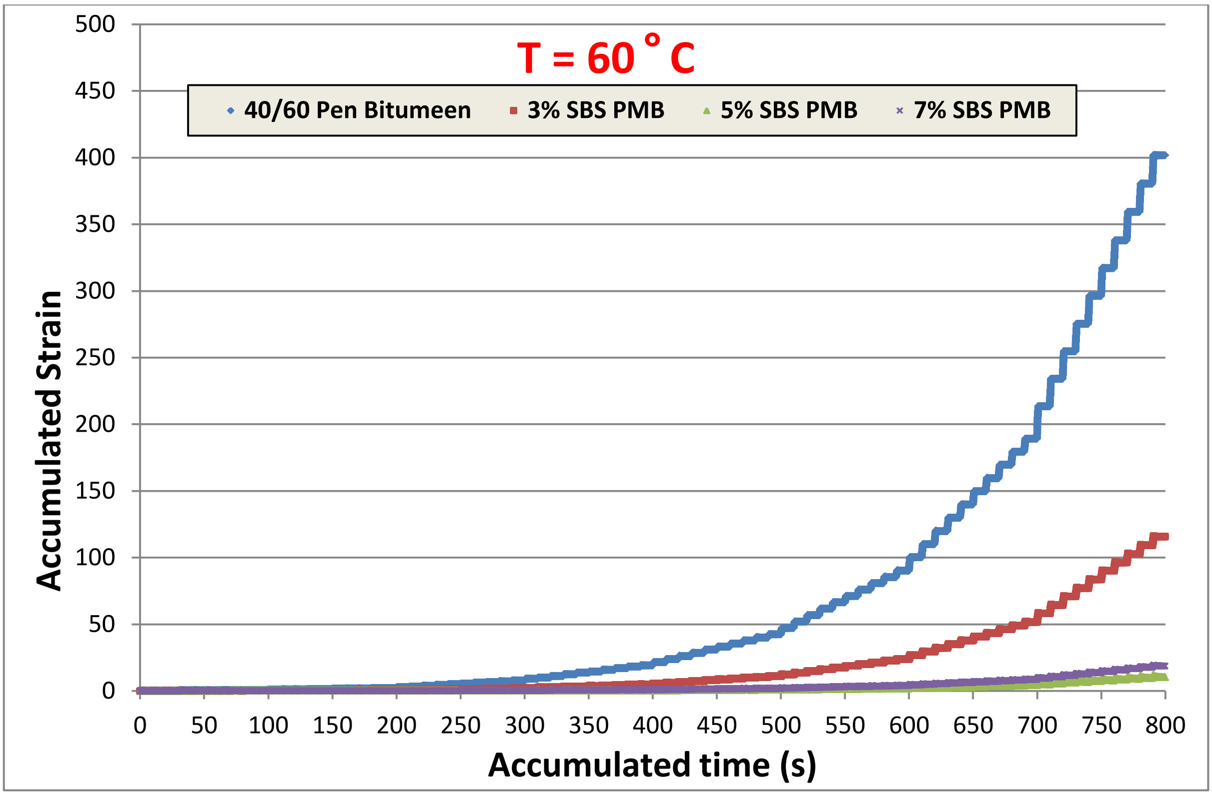


Figure 5.24: MSCRT response curve at 60°C

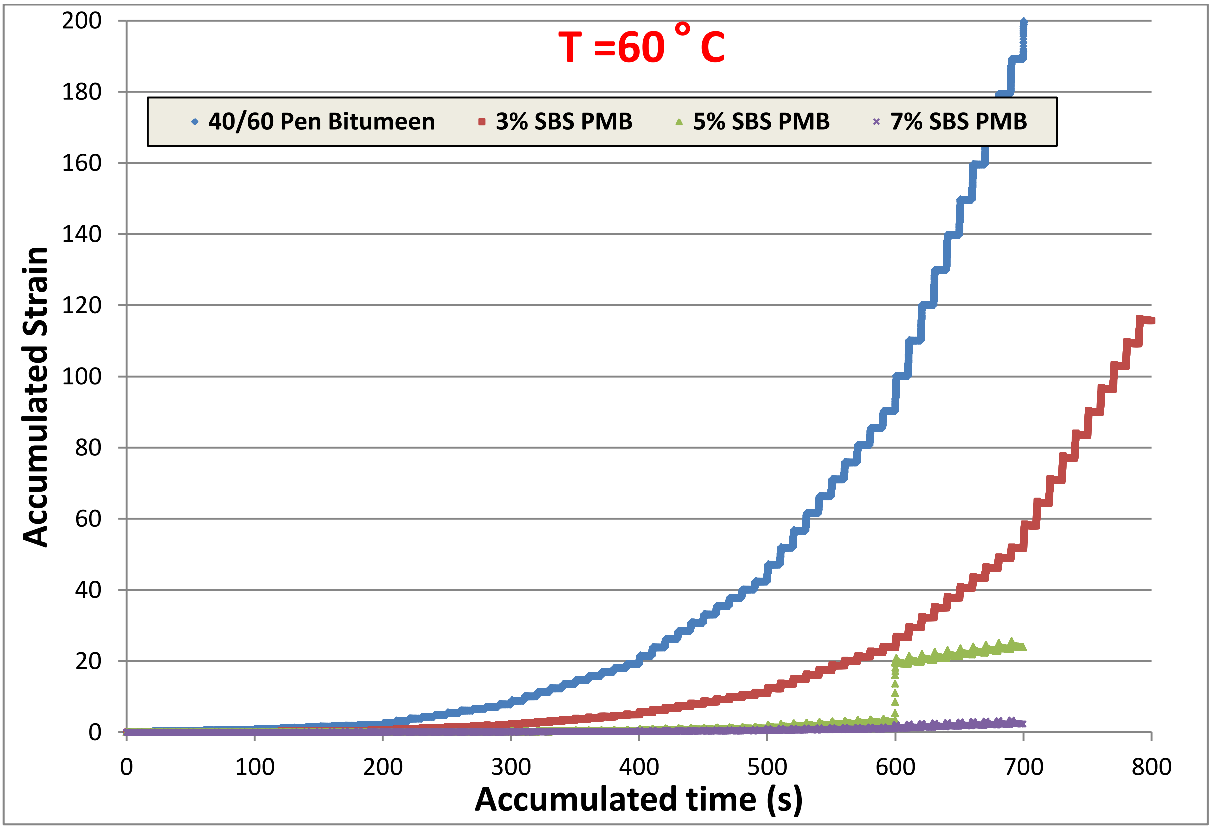


Figure 5.25: MSCRT response curve for PMBs at 60°C (after repeating the test)

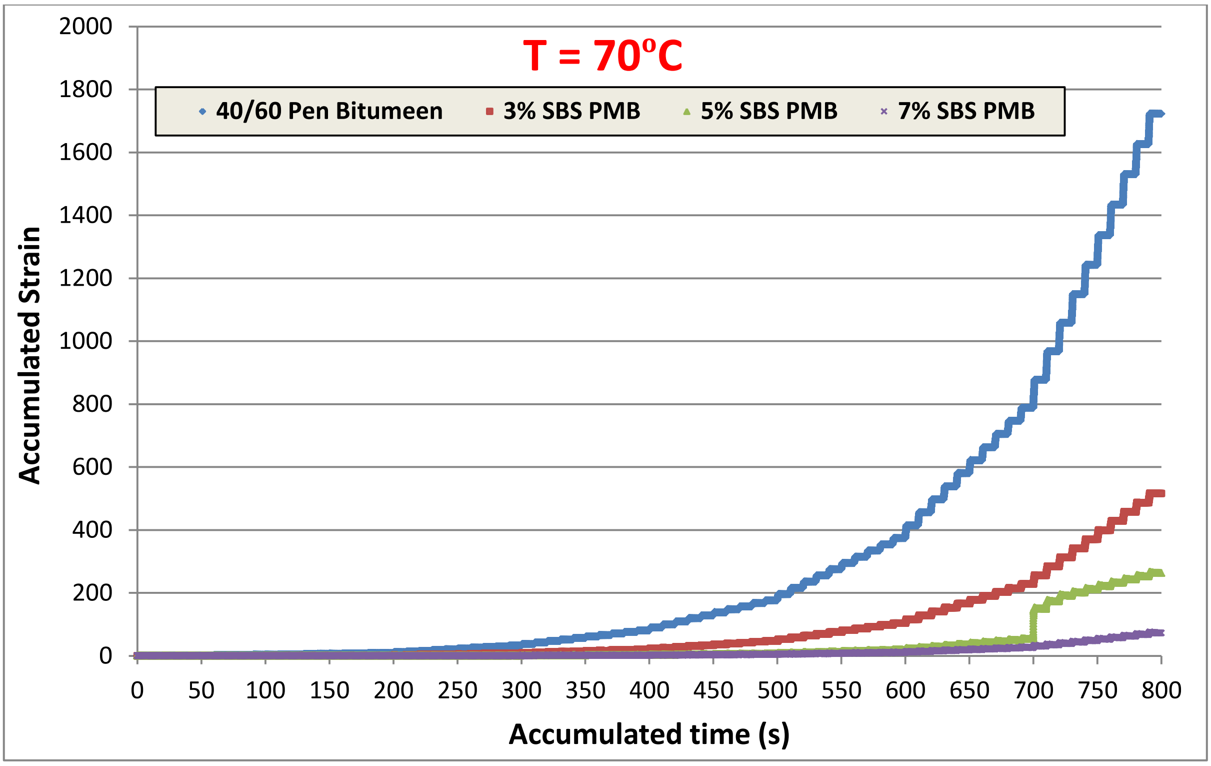


Figure 5.26: MSCRT response curve for PMBs at 70°C

5.3 Wheel Tracking Test (WTT) Results

It is possible to highlight that the mechanism of rutting in the WTT seems to be shear failure mechanism. Since the prepared mixture specimens were carefully manufactured under controlled laboratory conditions, including a sufficient degree of compaction, the densification mechanism is therefore less likely to be the cause of the deformation in this study. By the same token, shear failure mechanism is more likely to be the cause of the failure in the deformed slabs. This is because the wheel tracker at 60°C created small upward and lateral movements close to the loaded path, which may provide justifiable evidence. Moreover, the generated stress illustrated in Figure 5.27 may support and clarify this interpretation, in which the generated vertical and horizontal stress on a section of pavement tends to create a sort of deformation laterally, which is more likely to be shear stress, allowing the materials to move gradually with the repeated and uncontrolled contact pressure from the loading tyre. This causes plastic shear failure, particularly when a section of road experiences an overloading condition.

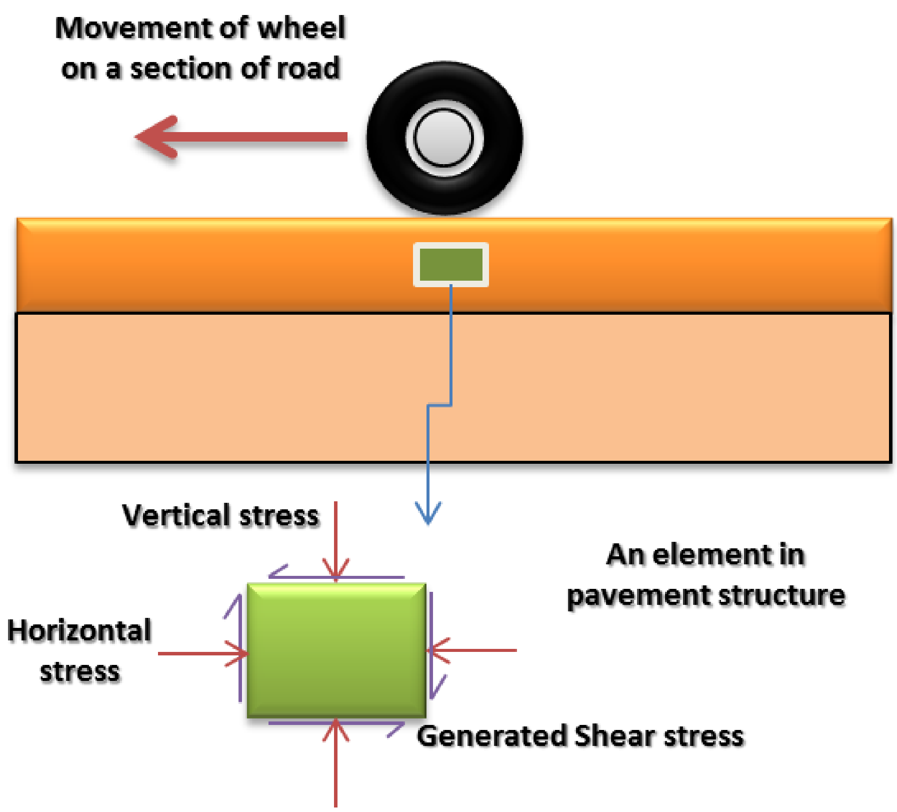


Figure 5.27: Acting out an element of asphalt pavement under traffic circumstances

WTT was carried out for nine slabs, which included three different percentages of SBS and conventional slabs (Section 3.2.5). Generally, it was found that the surface displacement was small on each of the slabs, despite being at 60°C. This may be related to use of BS parameters that only allow 45 minutes for the test duration, which possibly only generates a small rut depth. The principal aim of this test was to determine vertical displacement associated with rut depth, as described by authors such as Tatic et al. (2006), Garba (2012), Moses (2011) and Tayfur et al. (2007) as being a common distress under traffic conditions.

It is apparent from the measurements taken during the 45 minutes of the WTT that very few differences can be observed in surface displacement between the conventional mixture and the 3% SBS-modified mixture (Figure 5.28). Meanwhile, the same pattern can be seen between the 5% and 7% SBS-modified mixture, which is considered to be insignificant. This means that adding 3% SBS to the mixtures results in poor resistance, at which the maximum displacement was recorded at 2.16mm in the conventional mixture; while the mixtures at 5% and 7% performed considerably well, in which the minimum vertical displacement was 1.3mm by adding 5% SBS. However, it seems that adding 7% of SBS may not result in increasing resistance to rutting compared with 5% SBS. In this case, 7% SBS would not be economical to use, hence the SBS can be decreased by 2%.

The most striking point to emerge from the WTT results is that the maximum percentage of SBS did not performed reasonably well to be the optimum percentage (Figure 5.29). There are several possible explanations for this. Firstly, the most important may be related to the point that there should be a limit for adding SBS to provide an optimum resistance. This means that with excessive content of SBS, the outcome may be ineffective, or perhaps it even has negative effects resulting in inapplicable mixtures. This has also been experimentally found in past research by Khodaii and Mehrara (2009) as illustrated in the literature review (Section 2.7). Secondly, the type of aggregate utilized for the mixtures such as the aggregate located under the loaded area may also change the surface displacement. This view seems to be rather correct, as seen in a study conducted by Tatic et al. (2006) who believe that the type of aggregate and the particle sizes and shapes can change the performance of mixtures in permanent deformation. Thirdly, this is associated with the WTT itself; the outcomes vary between different testing devices and parameters, and there was a mix of the European and British standards in this particular test. Garba (2012) reveals that different test parameters and standards may influence the results.

On a larger scale, in order to determine the rut rate by taking a steady state along the last 15 minutes of vertical displacements (Figure 5.30), it appears that the lowest value of rut rate was recorded in 7% SBS. It can be noted that there are several fluctuations throughout the cycles, which means that deformed surface tends to recover, specifically in the 5% and 7% SBS-modified mixtures. This confirms that the added polymer has offered elasticity to the mixture. Additionally, despite the above mentioned factors, mixing proportions, aggregate type and gradation, as well as binder contents in mixtures are all influential with regard to permanent deformation (Section 2.3.1).

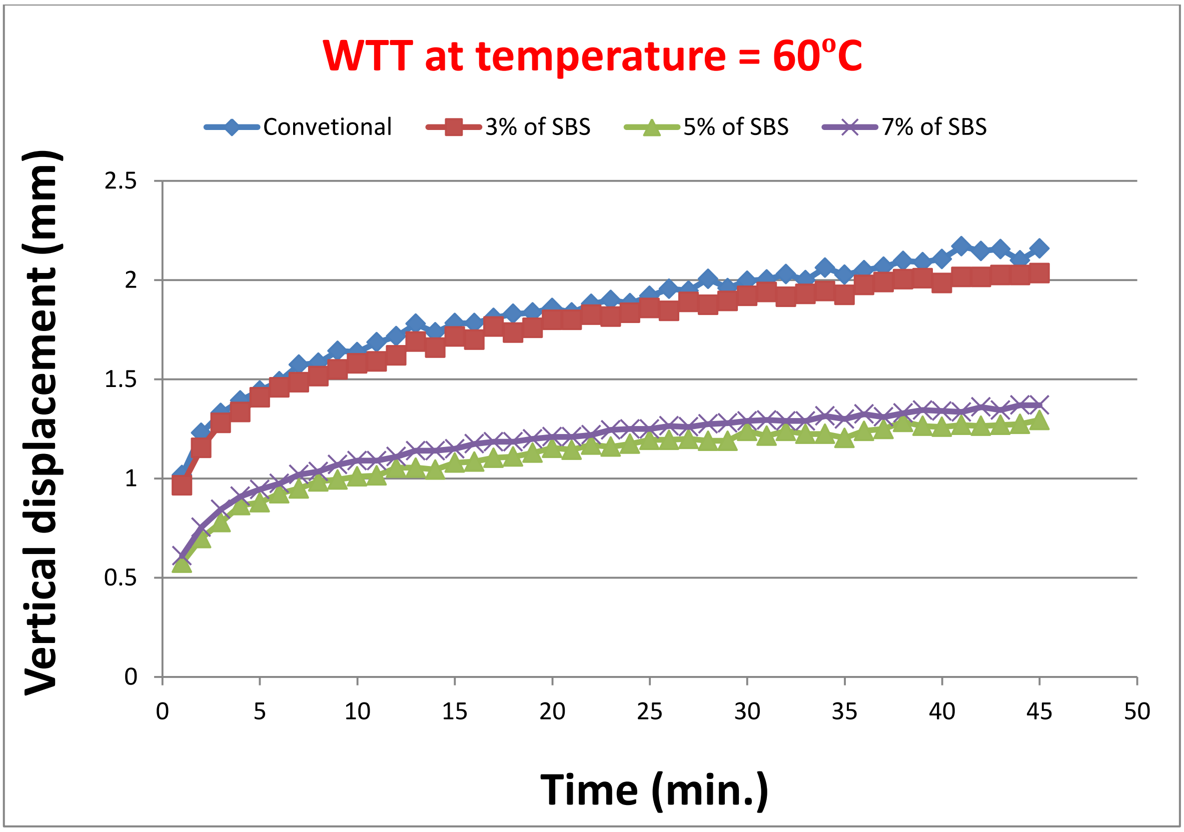


Figure 5.28: Rut depth versus time in WTT for different SBS contents and control

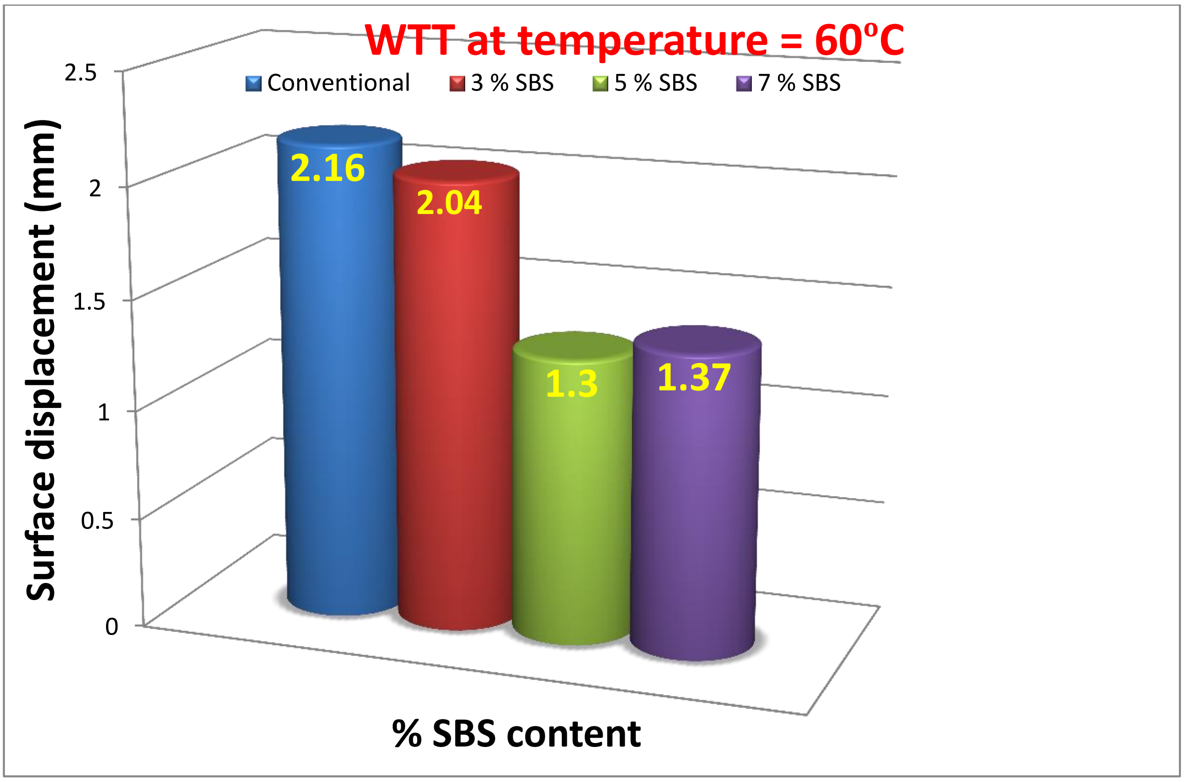


Figure 5.29: Illustration of the rut depths in different SBS contents at 45 minutes.

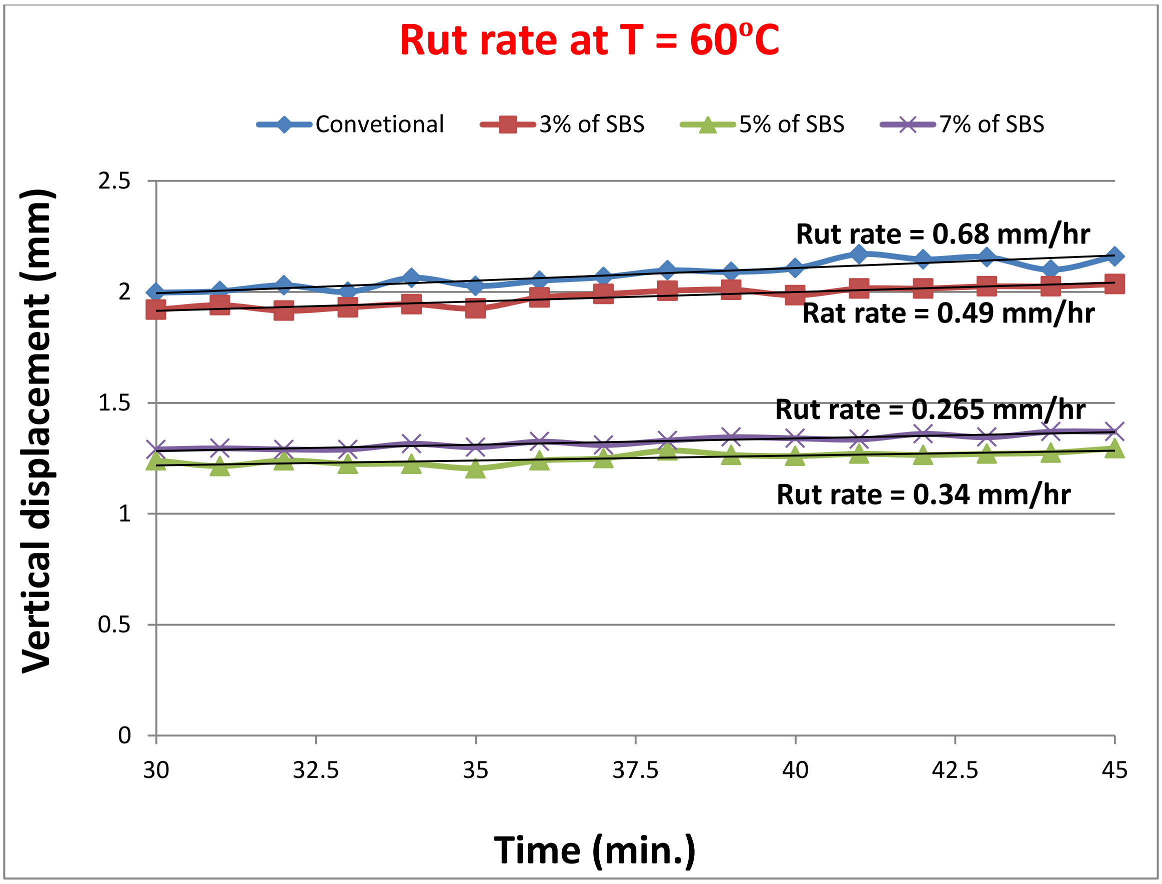


Figure 5.30: Rut rate in the last 15 minutes

5.4 Nottingham Asphalt Tester (NAT) Outcomes

5.4.1 Indirect Tensile Stiffness Modulus Test (ITSMT) Results

The ITSMT is temperature dependent and was carried out in the NAT to determine the dynamic stiffness modulus for different asphalt mixtures at 20°C using modified and unmodified mixtures. The experimental data in Figure 5.31 shows a significant increment of stiffness in different mixtures. The outcome illustrates gradual increase of the stiffness values in polymer modified mixtures compared with the conventional mixture, which means that adding SBS may have an effect towards improving mixture stiffness. It can be seen in Figure 5.32 that the lowest stiffness value was recorded in the conventional mixture (4629 MPa), while the highest value was in the 7% polymer modified mixture (9401 MPa). It can also be noted that the 5% and 7% SBS-modified mixtures indicate better performance of stiffness in comparison with the 3% SBS-modified mixture. Therefore, it can be highlighted that the optimum SBS content in this test is 7%. However, the variation in the stiffness value between these two mixtures (5% and 7% SBS contents) is not a considerably large difference. Thus, from an economic point of view, the mixture modified with 5% SBS may be more preferable as long as the difference in performance is small.

Since the stiffness of the bituminous materials is temperature dependent as illustrated in the literature review (Section 2.4), the added polymer may perform with better stiffness in high temperature circumstances despite reducing the stiffness value of mixtures. The added SBS may play an important role in compensating the decrease in stiffness in high temperatures. It is also hard to say whether or not added SBS may perform remarkably well at this considerably lower temperature (20°C). This is more likely to have an influence on the recorded results. This has also been experimentally shown in a study by Tatic et al. (2006) who demonstrate that stiffness value is affected by temperature changes, in which by increasing temperature, the stiffness value decreases although the polymer tends to perform better within the mixture (ibid). This would be the case in a section of road, in which the upper layer, i.e. surface layer, tends to hold the majority of the pressure (Section 2.4). This means selecting stiffer materials such as aggregate type and gradation in the mixture proportions, as well as binder for improving rutting performance.

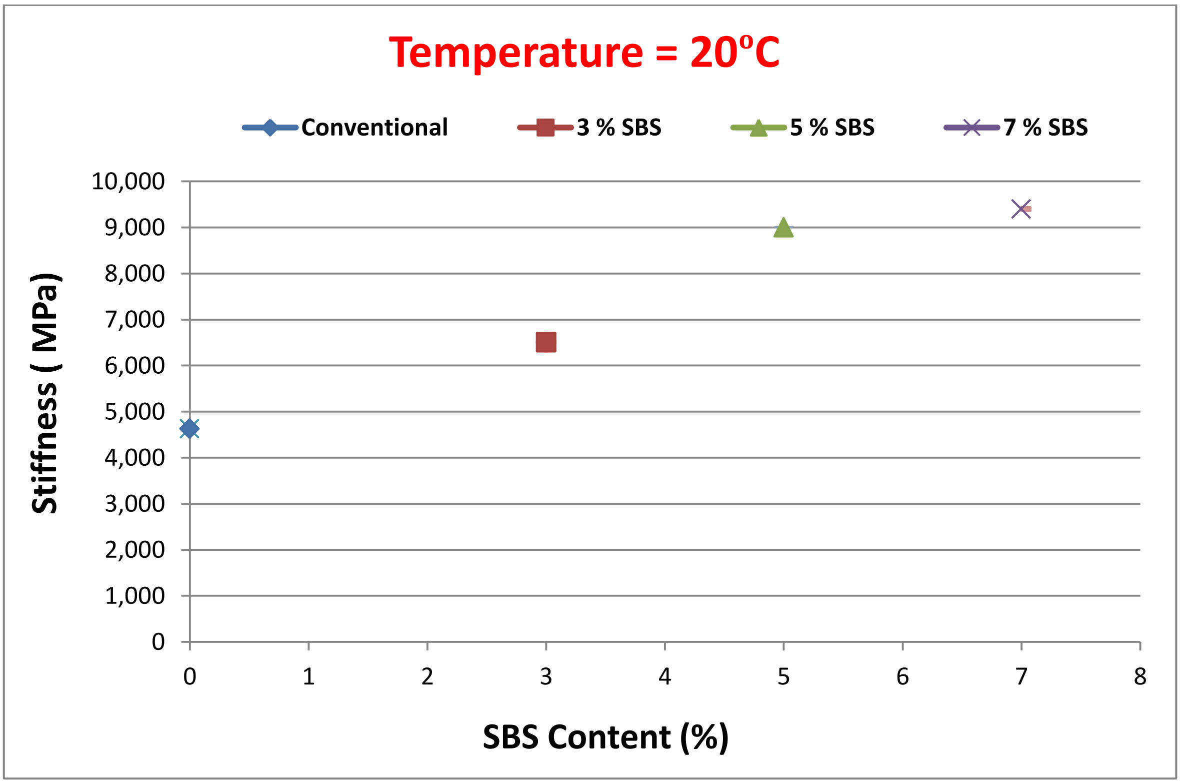


Figure 5.31: Relationship between stiffness and different SBS contents in ITSMT

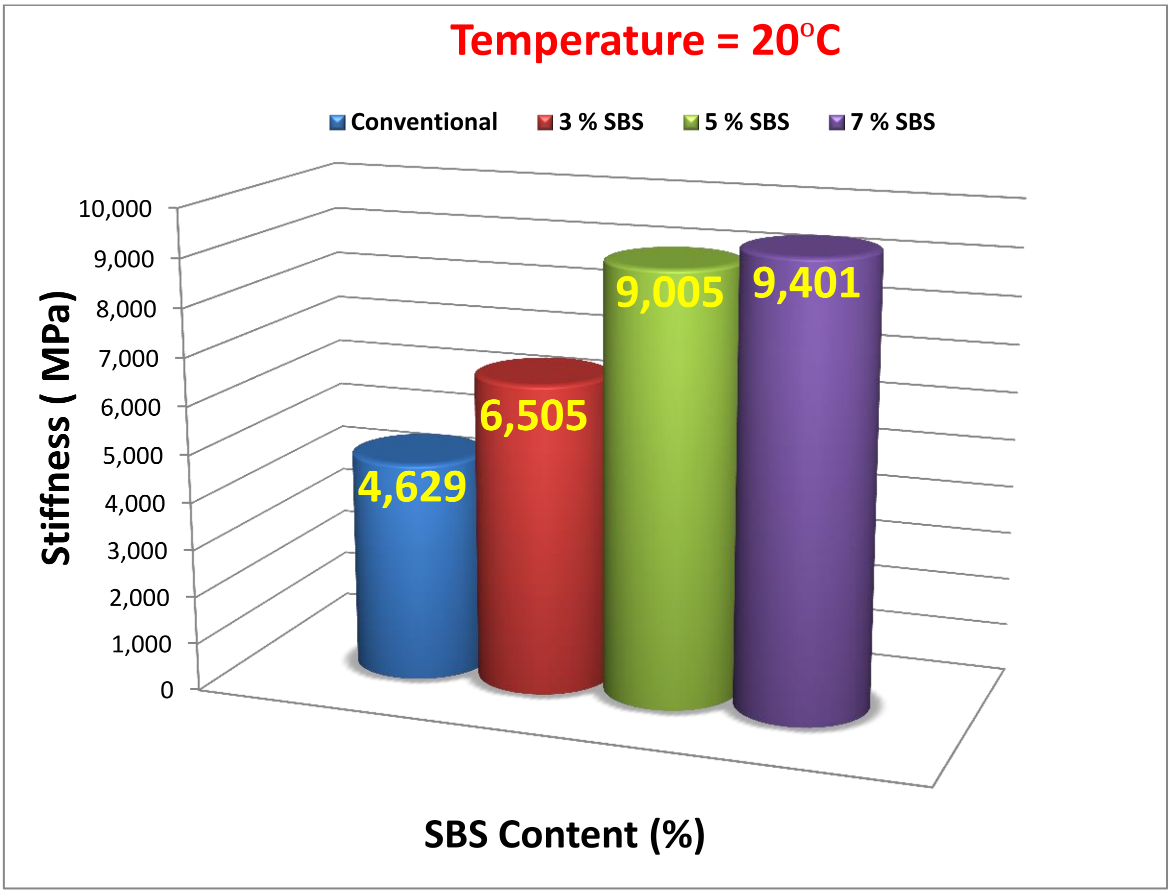


Figure 5.32: Illustrating the stiffness values from different SBS contents in ITSMT

5.4.2 Repeated Load Axial Test (RLAT) Results

The samples used in the ITSMT were also tested in RLAT. The axial strain is the permanent deformation associated with the axial strain ratio for the deformed height to the original height, which is directly obtained from a dynamic process in this test. As shown in Figure 5.33 the strain curves at 1,800 pulses appear almost parallel and these curves illustrate a slightly different trend to permanent axial strain, but in a more uniform manner. Test results bring to light a rather less permanent axial strain from the SBS-modified specimens with different levels of resistance, which means that the diverse polymer based samples have shown an improvement in strain resistance in the mixtures compared with the conventional mixture for the dynamic loading conditions associated with the number of pulses.

Furthermore, it can be noted that the presence of only 3% SBS leads the mixture to offer more strain resistance up to more than twice which is likely to be advantageous under the actual traffic conditions. Furthermore, the modified 5% and 7% SBS mixtures resulted in further increase of the strain resistance (Figure 5.34), which resulted in less axial strain (0.81% and 0.76% respectively as maximum values).

As shown in the graph, the strain lines in the modified 5% and 7% mixtures almost increase in parallel; they are quite close to each other with a relatively small increase in the 7% SBS-modified mixture. This inevitably means that it is rather difficult to establish that the optimum value of SBS is 7%. Alternatively, the polymer content of 5% may provide almost the same performance for permanent accumulated strain as its counterpart (7%). This means that from an economic perspective, it is more likely that adding 5% SBS may provide an almost similar outcome as 7%.

Although the obtained outcomes may reasonably present the role of each percentage of polymers, it is necessary to explain that the temperature of the test (30°C) may have influenced the actual performance of SBS towards a poorer performance compared with high temperatures, in which cases SBS tends to show possibly better performance against permanent strain. This is in agreement with a comprehensive study by Tatic et al. (2006) showing that in this particular temperature (30°C), SBS is less likely to provide an appropriate performance compared with high temperatures such as 50°C, in which the polymer tends to work preferentially well to permanent deformation (ibid). In addition, changing other proportions of the mixtures such as aggregate gradation and type and the binder content may also change the resistance of the mixture.

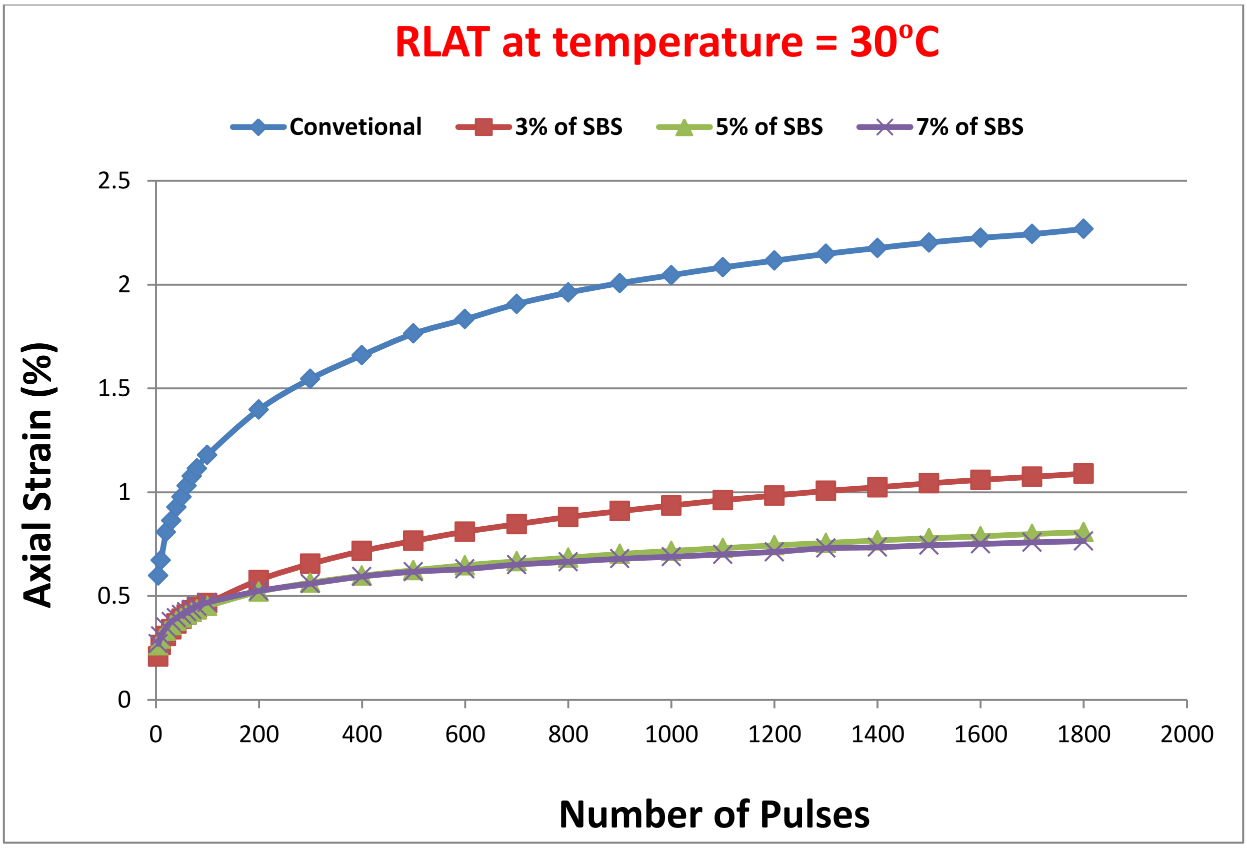


Figure 5.33: Axial strain versus number of pulses in RLAT

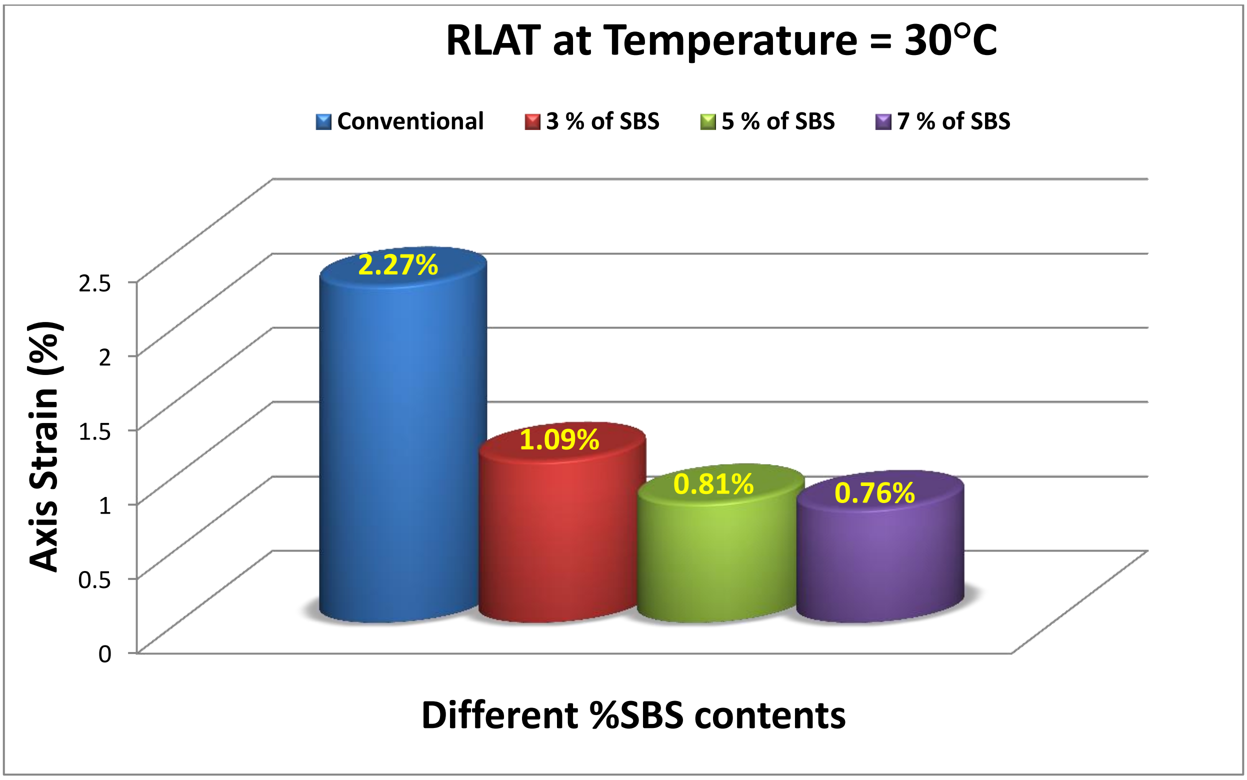


Figure 5.34: Performance of different SBS contents in RLAT

5.6 Discussions and Review of Findings

There are several possible explanations for the obtained results for each of the test outcomes. The MSCRT is underlined as an appropriate test for evaluating PMBs, in which its parameters are significantly reliable to assess binder susceptibility to permanent deformation. The results of this test appeared encouraging as a basis for the mixtures in selecting optimum PMBs, taking into account the economic aspect before running the mixture tests. It can be stated that reducing non-recoverable compliance (J_{nr}) by half typically reduces rutting by half too (Section 2.8.2). This can be obtained by using a powerful percentage of SBS to be added to binders, i.e. 5% or 7% SBS, to achieve possibly the highest resistance to deformations. It is therefore likely that this relation in the MSCRT may have an acceptable degree of validity in finding the best SBS-modifier. In other words, the outcome of adding an excessive percentage in SBS dosage may be ineffective, or perhaps may even have consequences of being inapplicable and producing uneconomic binders or mixtures.

Whilst the findings associated with the elastic response in MSCRT confirm an acceptable elasticity associated with the recovery value (%R), it seems that the binder elasticity alone may not adequately prevent deformation within the mixtures as reflected in the mixture tests. Therefore, it is essential to investigate a relationship between binder strain recovery within the mixtures to improve rutting resistance.

In order to integrate the different test results into an overall understanding of the subject, these understandings need to be further related to previously published studies in terms of similarities and differences with their rationale to clarify the main hypothesis and to meet the primary aims and objectives of this research project; hence coefficient correlations have been drawn to clarify the main links between binder and mixture tests and the mixture tests themselves. Figure 5.35 shows a relationship between the permanent strain and surface displacement in both of MSCRT and WTT respectively, in which the correlation coefficient is about 0.658. It is clear that the strain and rut depth tend to decrease as the percentage of SBS increases. Since these two tests were carried out at the same temperature (60°C), it could thus be suggested that their parameters are related to rutting performance (Sub-sections 2.8.2 and 2.8.3).

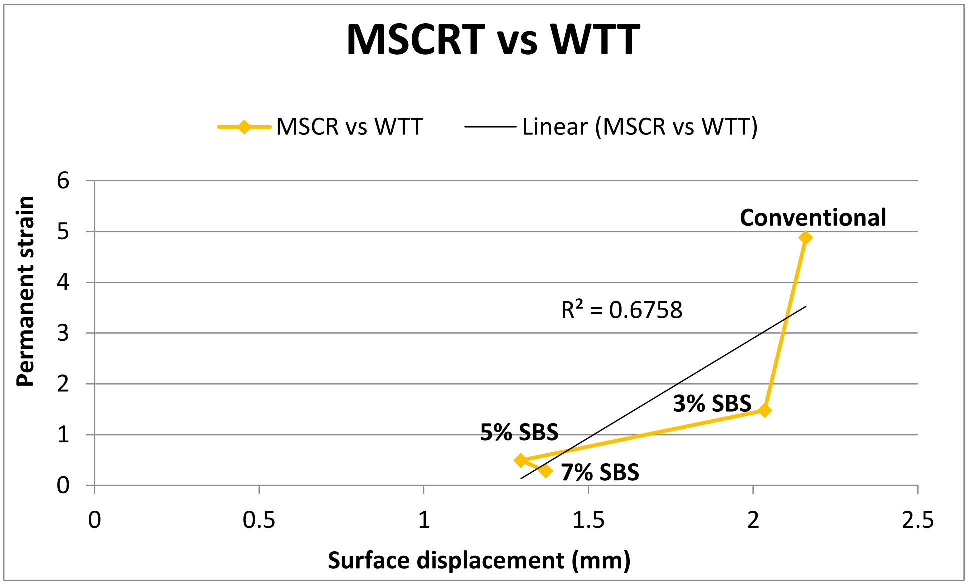


Figure 5.35: Permanent strain versus surface displacement

Furthermore, the correlation coefficient illustrated in Figure 5.36 is 0.875 in MSCRT versus ITSMT, in which by adding SBS, permanent strain decreases with increasing stiffness values. This confirms the hypothesis of relationship between stiffness and rutting as critically explained and reviewed in chapter two (Section 2.4), which also mentions that increases in stiffness value could be attributed to the increase in rutting resistance. One of the problems that emerges from this finding, however, is that an acceptable stiffness of binder may not result in an acceptable mixture that is reasonably stiff and survivable against rutting, because of aggregate contribution (Sections 2.4 and 2.3.1.2), and also because of the imprecise relationship between stiffness and rut resistance. These correlations have received a lot of attention by previous research although the aggregate influences may change the performance of the mixture tests.

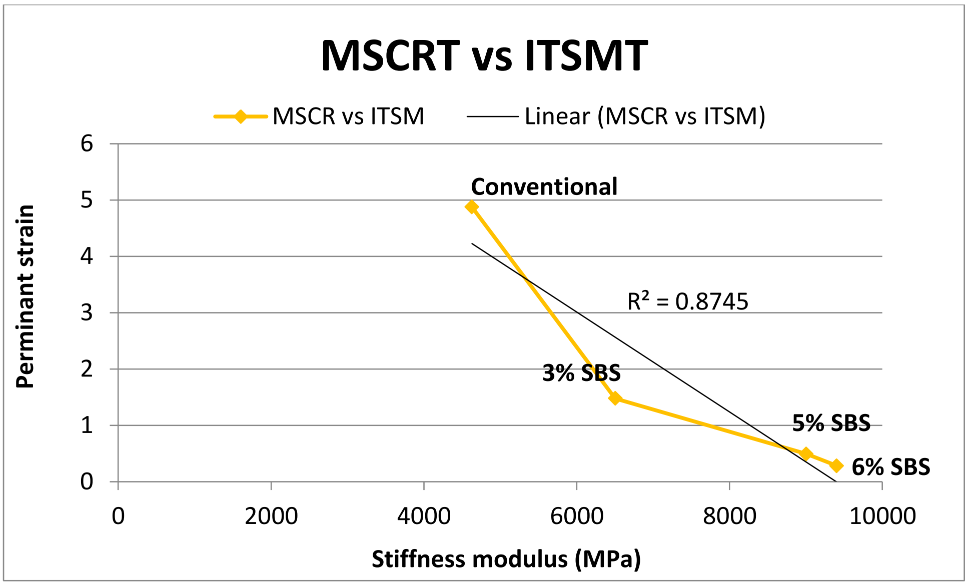


Figure 5.36: Permanent strain versus stiffness modulus

Moreover, Figure 5.37 demonstrates a much better relationship between permanent strains in MSCRT versus axial strains in RLAT. The coefficient correlation displays the correlation due to the addition of SBS, in which by adding polymer content, both permanent strain in binder and axial strain in mixture tend to decrease significantly. Likewise, this combination link provides some support for the conceptual premise that a susceptible binder to permanent strain tends to give rather similar deformation to the mixtures (Section 2.3.1.2).

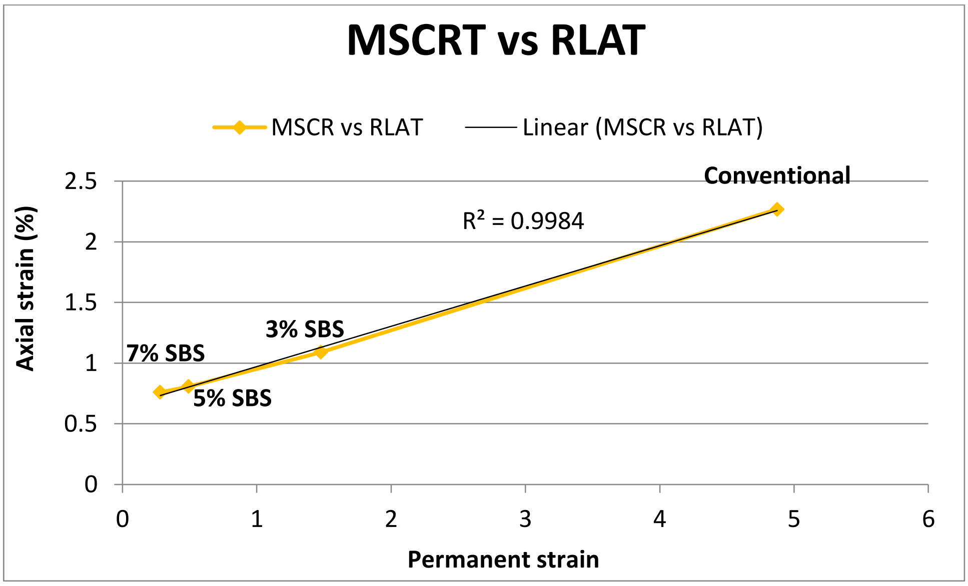


Figure 5.37: Axial strain versus permanent strain

Regarding the mixture tests, Figure 5.38 indicates that increasing stiffness in the ITSMT results in decreasing rut depth favourably when SBS content increases to its high percentages, i.e. 5% and 7%. The coefficient correlation is 0.927, which is higher than that of the WTT versus RLAT (0.642). The relationship shows the association between vertical displacements versus axial strain (Figure 5.39), indicating that the decrease in rut depths of the mixture slabs due to the addition of SBS is followed by a decrease in axial strain of the cored cylindrical samples. However, one problem that emerges from these findings is that the 5% SBS content in WTT performed in better rut resistance than 7%, while this did not occur in the RLAT. This may be related specifically to a degree of compaction in the edges of the slab from which the cored cylinders had been taken, or perhaps the location of cored specimens had been influenced by WTT (illustrated in Section 1.3). Similarly, an increase in stiffness modulus in ITSMT due to the addition of SBS of the samples is followed by decreased axial strain in RLAT, as shown in Figure 5.40, at which the coefficient correlation showed an acceptable linear relationship (0.847) between these two properties. This is considered to be a slightly higher correlation in which adding polymer decreases permanent strain, while the stiffness decreases in mixtures (Section 2.4).

It seems that at least there is an indirect connection between elastic properties and permanent deformation: a higher stiffness layer will spread load better so the stress applied to layers below will be less. Thus, they can be expected to suffer less permanent deformation. However, the reduction of plastic response (i.e. a more elastic response) during load-unload cycles will be significant. Therefore, it is not that the elastic response changed. It is that the plastic component has reduced (illustrated in section 2.4).

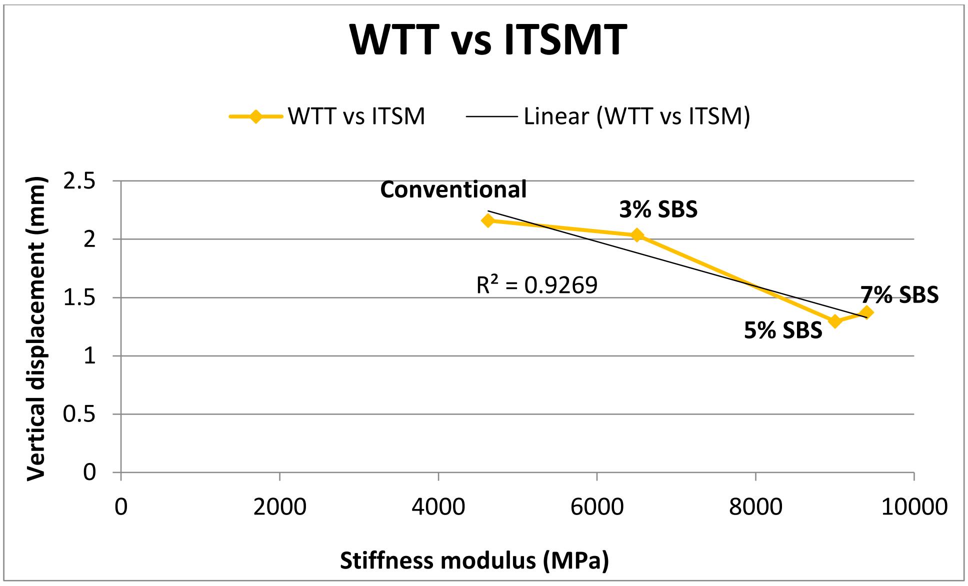


Figure 5.38: vertical displacement versus stiffness modulus

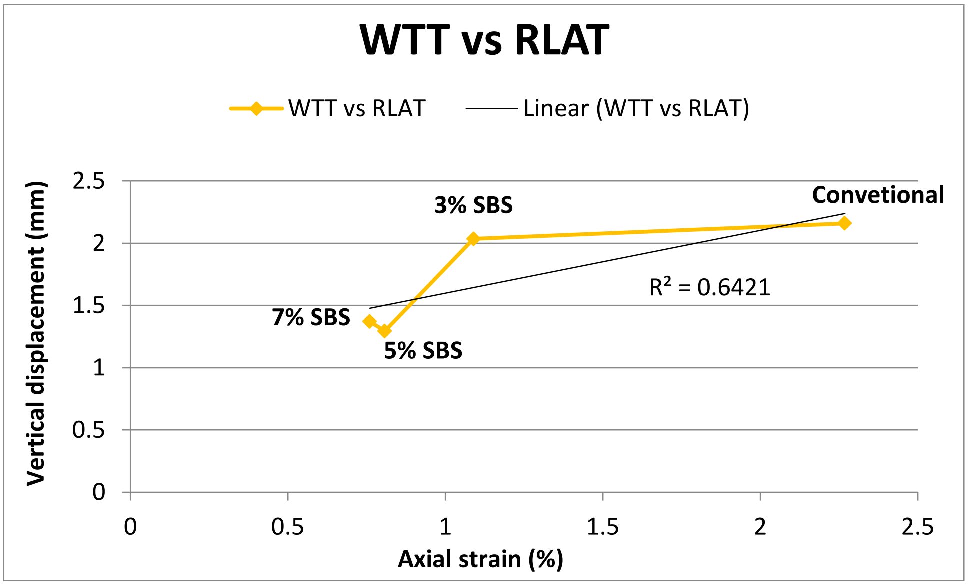


Figure 5.39: vertical displacement versus axial strain

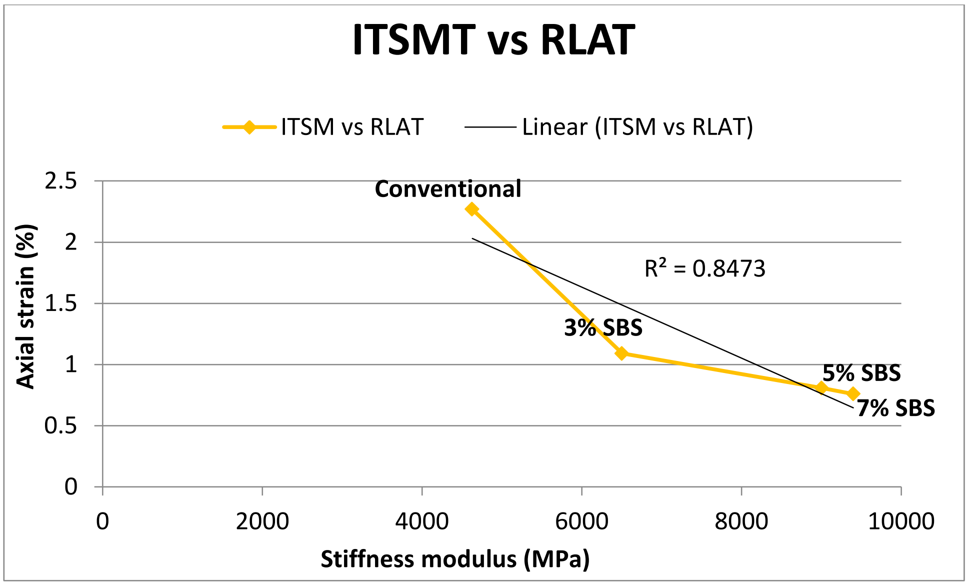


Figure 5.40: Axial strain versus stiffness modulus

Although the results bring to light that both 5% and 7% SBS mixtures are preferable for providing as reasonably high resistance as desired against permanent deformation, they may not confirm the sought after outcomes of the MSCRT as a binder test. Despite the significant contribution of polymer, the influence of aggregate within the mixtures tends to make noticeable variations which may not necessarily result in the similar performance compared with the MSCRT outcome. The findings of effectiveness of binder will doubtless be much scrutinized, but there are some immediately dependable factors that have to be considered in terms of the quality of aggregate (identified in Section 2.3.1.2), particularly in the case of this study, in which the aggregate was designed for the surface layer of pavement.

5.7 Summary of Key Points

This chapter discussed each of the four test outcomes analytically in order to meet the main aims and objectives of this study. Within the findings of the current study, the most significant links have been presented. The integration of the main understandings are explained and assessed by comparing them to the previously reviewed research to show the consistency of agreements and disagreements. The effect of SBS is found to be powerful in improving the binder and mixture resistance to permanent deformations. Furthermore, the degree of adding SBS has been highlighted as 5% to 7% with economic considerations given priority.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.0 Overview

This chapter highlights the main conclusions obtained by summarizing the gathered results followed by an underlining of the most significant outcomes of each test and the key findings arising from an overview of the full united data set. Furthermore, this study extends the knowledge of the main conclusions to offer a number of important implications for both practical application and future research.

6.1 Summary of Results

Based on the test results, it was found that the binder test is able to efficiently determine the binder's actual susceptibility to permanent deformation by representing the most significant parameters, such as non-recoverable compliance and recovery percentages, which indicated an increase in rutting performance by adding polymer. While the MSCRT data identified that polymer percentages of 5% and 7% performed preferentially at temperatures of 50°C, 60°C and 70°C, these percentages also yielded rather similar performances in the three asphalt mixture tests.

It is obvious from the asphalt mixture tests (WTT, ITSMT and RLAT) that the SBS contents of 5% and 7% are able to offer the highest performance compared to the ordinary mixtures in terms of vertical displacement associated with rut depth, stiffness modulus value and axial strain. A possible explanation for this may be related to recovery improvements to the binder achieved by polymer in the mixtures, particularly when temperature increases, which has been stated by previous research. However, the influence of binder elasticity on mixtures is too complex to be simply explained, because of the diverse contributions to elastic and plastic response. This means that binder elasticity alone might not be an adequate inhibitor of permanent strain nor improve overall mixture performance.

This project set out to determine the fundamental effects of SBS-modified bituminous mixtures toward obtaining an improved model of mixture to show an acceptable performance against permanent deformation. Returning to the hypothesis posed with the key questions at the beginning of this study, it is now possible to state, based on both binder and mixture test data, that the PMBs were able to deliver an appropriate rutting resistance. It has been shown that the parameters obtained from the binder and mixture tests indicated favourable performances, and illustrated a reasonably encouraging link between some of the binder and mixture properties using the same SBS percentages and binder grades, which will assist in the design of mixtures. This earlier observation helps to explain why a high correlation is revealed between the laboratory test parameters, such as higher %R values and smaller J_{nr} values, and rutting resistance specifically with the favourable SBS contents.

The mixture tests, specifically the WTT, revealed how shear failure could be identified, as it was a consequence of this test, and how it could be compared with the densification cause. It has also been found that both the stiffness of mixture samples and resistance to axial strain (in RLAT), were obtained at 7% SBS dosage in these two tests.

Nevertheless, in the light of the results of the four tests, it would be unfair to underline, in any concrete way, that 7% is the optimum SBS percentage. Although this percentage indicated a reasonably acceptable rut resistance, the performance was rather close to that of 5% SBS-modified mixture. Therefore, economically, it has been found that 5% of polymer content is the most preferable dosage rate needed to attain a reasonably acceptable rut resistance.

Overall, the findings observed in this study mirror those of the previous studies that have examined the effect of PMBs in mixtures, specifically those matching assessed binder behaviour to mixture tests. In contrast to earlier findings, however, no evidence of aggregate influences was detected in this study. Nevertheless, the effect of aggregates highlighted in previous studies appears to be significant so that its possible influence cannot be ruled out, as it was not a parameter varied in this project.

6.2 RECOMMENDATIONS

6.2.1 RECOMMENDATIONS FOR INDUSTRY/APPLICATIONS

Despite its exploratory nature, the importance of this study offers some insight for practical implications for the author's home country, i.e. Kurdistan. The most significant beneficial applications are as follows:

- Since there is an increasing tendency toward the use of polymerized binders, this research provides guidance regarding the main properties of PMB, both separately and within the mixtures, and the main concerns for application in hot environments.

- The present study identified the most significant tests that could be used by pavement authorities; for example, the MSCRT gives a better indication of rutting susceptibility, allowing an economic percentage of SBS to be selected for the manufacturing of asphalt mixtures.

- The potential has been demonstrated for the experimental tests carried out in this project to be used to assess the characteristics of the mixtures that are utilized in the construction of roads. For example, the stiffness modulus obtained as a main finding of the ITSMT can be suitable as one of the parameters for the design of pavement layers. Meanwhile, the RLAT reflects the plastic response to dynamic traffic loading.

- Previous studies have indicated that overloaded roads may generate permanent deformation. Therefore there should be a limit of capacity for any road to survive in order to control any extra loadings associated with traffic volume, which may cause the bituminous materials to deform, especially in the surface layer.

6.2.2 RECOMMENDATIONS FOR FURTHER FUTURE REASEARCH WORK

This research has thrown up many questions in need of further investigation. Several points outlined below remain open to question at present:

- Since different test temperatures have been used in the laboratory, it is not exactly clear at which temperature a SBS-modifier begins to appropriately improve the mixture's elastic response. Consequently, further investigation is needed in running ITSMT and RLAT at higher temperatures, such as 40°C to 50°C, to obtain more details.

- A further study of the use of the MSCRT with more focus on diverse loading and unloading times is recommended. This could indicate a more logical means of showing the influence of binder elasticity on permanent deformation.

- A greater variety of binder (with different penetration grades) and mixture tests (with different types, gradations and shapes) is recommended to evaluate and examine the impact of the bitumen elasticity on the bituminous mixtures' permanent deformation performance, so as to develop a clear understanding of the association between binder elasticity and mixture behaviour. Therefore, further studies, which take these variables into account, will need to be undertaken.

- High temperature needs to be maintained during the SBS-mixing process, which may cause difficulty and complexity in terms of workability or energy inefficiency. Several studies highlight the use of warm mix asphalt additives mixed with SBS to produce workable mixtures with acceptable rut resistance. However, more research on this subject needs to be undertaken.

- Another possible area of future research would be to investigate how moisture content may influence permanent deformation. This is highlighted in several studies as a key factor that affects the properties of binder, additives and aggregate in a mix, as well as their proportions.

- Since Finite Element Model approaches have played a great role in previous studies, further research of that type could be combined with experimental programmes in order to make a comparison between both outcomes, so as to assess the ability of modified pavement layers to resist permanent deformation.

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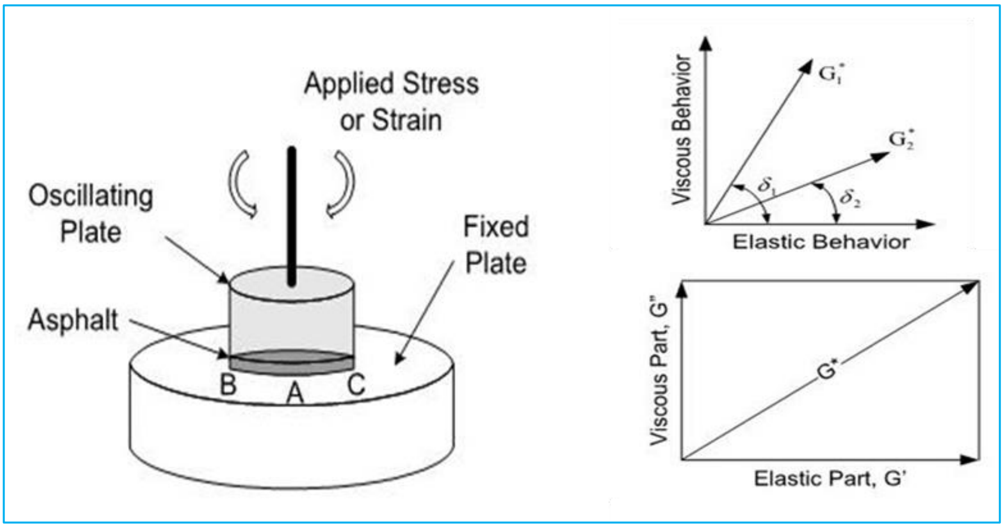
APPENDICES

Appendix A: Dynamic Shear Rheometer (DSR) Test for Bitumen

DSR is considered to be the most fundamental test for measuring rheological properties of binders (Airey 2004; Ping and Xiao 2009; Khan 2008; Lavin 2003). This test represents viscous and elastic behaviour of bitumen in different illustrative parameters between intermediate and high temperatures. As shear stress is applied sinusoidally, from the amplitude and applied frequencies, the changed outcomes of deformations from the sandwiched plates between oscillating and fixed plates are observed. Furthermore, complex shear modulus (G*) by the provided frequency is obtained, which is a ratio of shear stress and strain. To find the degree of elasticity, phase lag or phase angle (δ) is determined, which is demonstrative of shear stress and shear strain. For a purely elastic material, there will not be a difference between them, while this relation would be represented by 90° of phase angle on the sinusoidal graph in viscous binders (Figure A.1). In other words, 'since asphalt binders are viscoelastic, the phase angle between the shear stress and shear strain is between 0° and 90°'. What is meant by this is that a 0° phase angle illustrates elasticity and 90° indicates viscous liquid (Lavin 2003:30).



(a) (b)

Figure A.1: (a) DSR Test (b) Complex modulus (elasticity and plasticity) (Ping and Xiao 2009)

Airey (2004) points out that assessing accurate rheological properties of binders needs a DSR test, although there are also some traditional tests for penetration, viscosity, ductility and softening point temperature. The reason is that the outcome does not fulfil the representation of actual rheological characterization, particularly in the case of modified binders.

It has been indicated that the rheological properties of binder can be identified by drawing a master curves diagram, and relaying a complex modulus and phase angle by using shift factor values in a defined temperature. Based on experimental studies, it was noted that diverse shifting results can be obtained depending on different temperatures and frequencies (Figure A.2). Within these, a numerical shift formed a proper fit in presenting measured and modelled data (Yusoff 2012).

Additionally, a Black diagram is used to exhaustively demonstrate the whole test parameters, in which stages are compatibility represented. It seems that little research has been carried out in developing this diagram, but that which has been undertaken states that it is an illustration of the phase angle (δ) and complex shear modulus (G^*) (Figure A.3), which represent any dynamic experiment (Yusoff 2012). It has been considered that this diagram is like a finger print in cases of low temperatures with high frequencies and vice versa, which is illustrative of the rheological properties of binders. To that end, a Black diagram is used to show inconsistencies in rheological data collection (Airey 2002a).

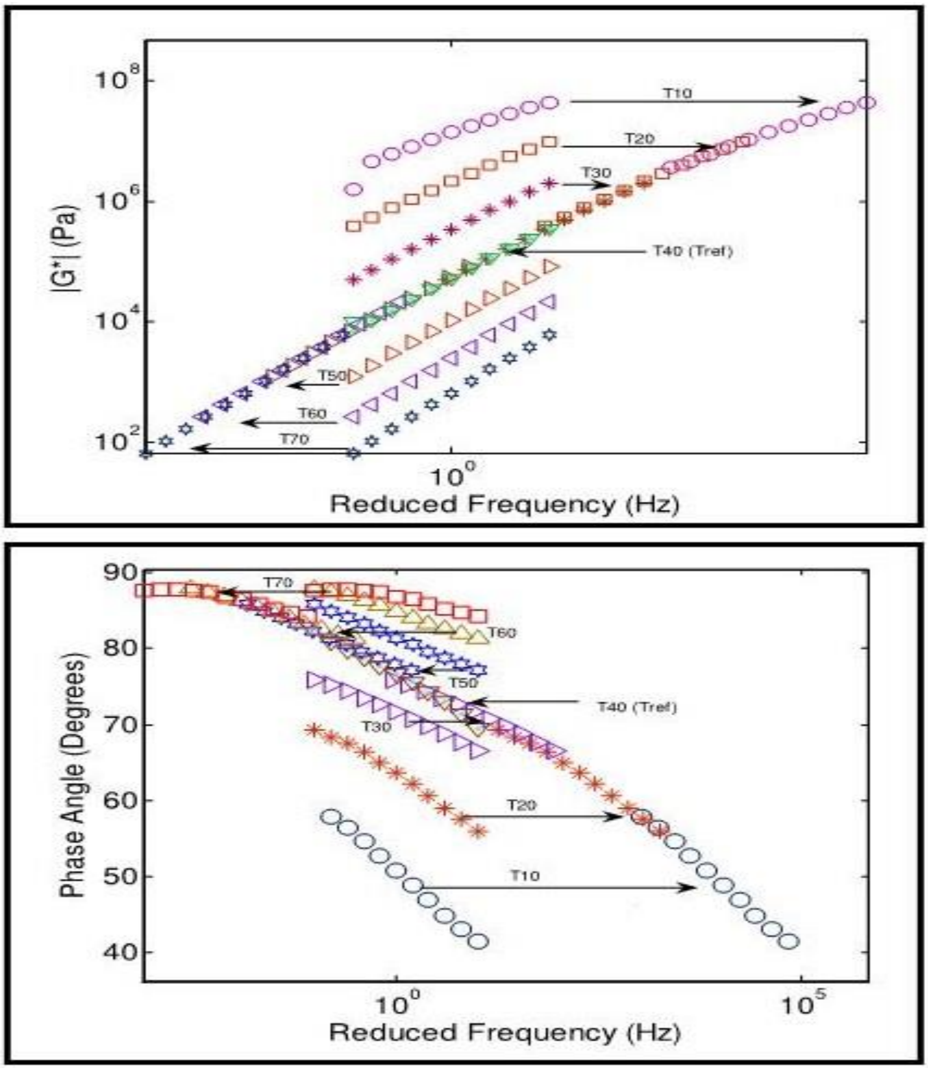


Figure A.2: Construction of the *G** and master curves (Yusoff 2012)

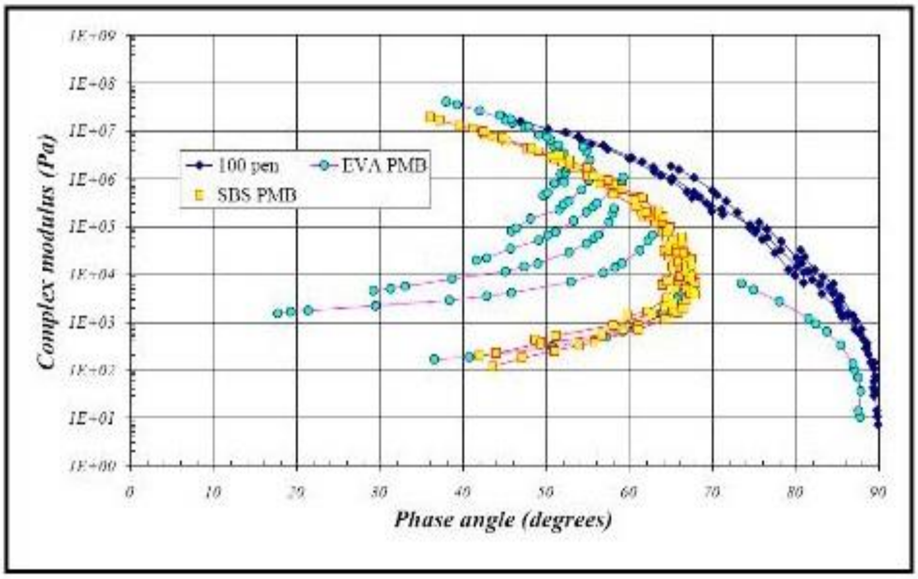


Figure A.3: Example of Black diagram using modifiers (Airey 2002a)

Appendix B: Mixture Proportions

Traditionally, the fundamental components of the HMA are bitumen and aggregate including void content where volumetric considerations are identified. Typically, aggregate covers nearly 95% of mass of the asphalt mixture components, while what remains is the bitumen content (5%). Volumetrically, as NCHRP (2011) reports, a mixture consists of 85% aggregate, %10 binder and 5% of air voids (Figure B.1). Correspondingly, to improve a specific or the overall performance of the asphalt mixtures, it is preferable to add modifiers including polymers, crumb rubbers, fibres or whatever modifier with reasonably optimum amounts that could improve a specific characteristic of asphalt.

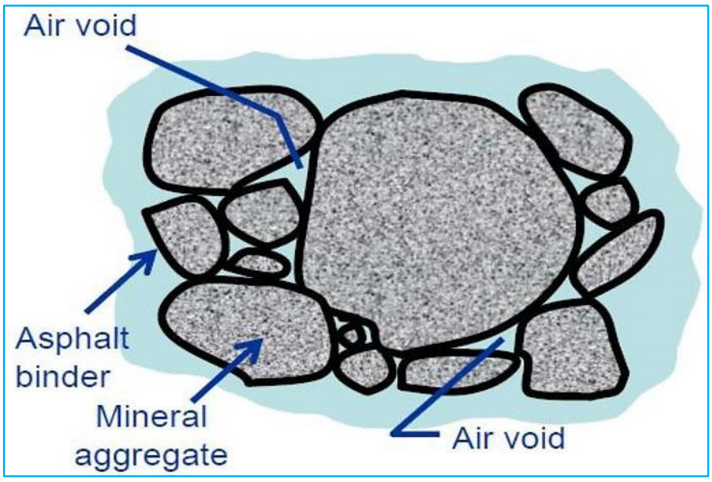


Figure B.1: The main components of asphalt mixture

B.1 Bitumen

Binder plays a vital role in asphalt mixtures as it connects different particle sizes of aggregate together. Essentially, it is refined from crude oil and it is mainly consist of carbon and hydrogen as well as some sulphur with oxygen. What is significant in binder is temperature, which is strongly in relation with its performance as its viscoelastic material represented by grade of the bitumen, particularly in the HMA. Generally, binder tends to be viscos in high temperatures, whereas in low temperatures would be more elastic, in which physically the viscosity tends to increase (Figure B.2). In this case, the stiffness performance is reduced. On the contrary, the stiffness tends to increase leading to increase the brittleness of mixtures (Lavin 2003).

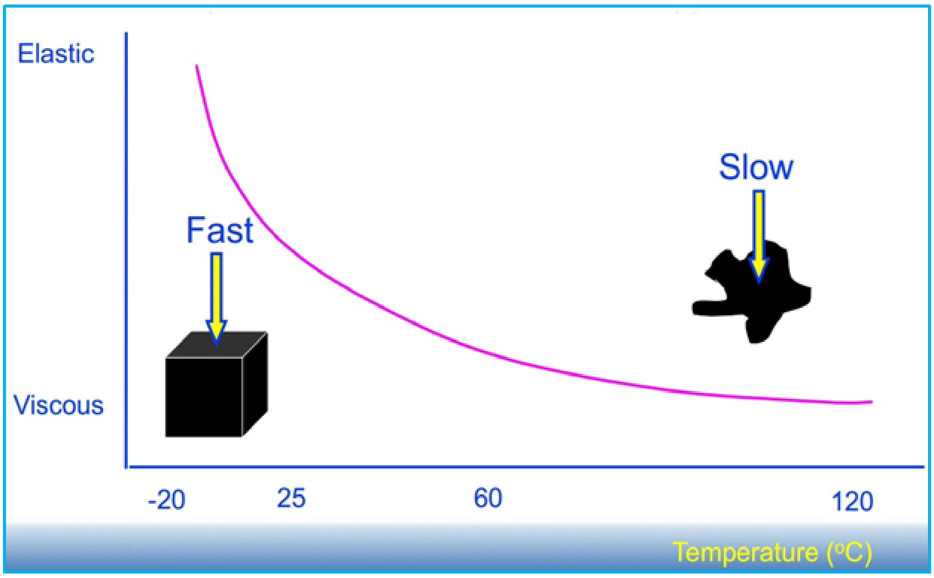


Figure B.2: Influence of temperature versus viscosity binder viscosity (Gates 2010).

There are various grades associated with binders which are used according to climate circumstance. The system utilized in the UK is penetration grading system which is 35-50 pen. Identifying the grade of binders can play a key role in asphalt design. The bitumen becomes softer in case of higher penetration and becomes harder in low penetration (BS EN 12591 2009).

Due to changes in the environmental circumstances, binder is more likely to perform inappropriately and may not fulfill the desired role. The problem is that, if the temperature becomes unstable, then it is certain that some differential deformation will be present. Perhaps the bitumen itself is pretty uniform but the penetration grade certainly is not reasonable with this particular environment. This may necessitate a particular type of modifier as an additive to improve the rheological properties of the bitumen which may lead to reduce risk of permanent deformation (Khodaii and Mehrara 2009; Ping and Xiao 2009).

B.2 Aggregate

Aggregate constitutes a vital part of the asphalt mixtures which is the major part, around 85% by volume. It has been proven that aggregate play a key role with regard to the overall performance of mixtures. In general, it is categorized into three types depending on their particle sizes. These include fine aggregates, coarse aggregates and mineral fillers. Aggregate passing through 2.36mm sieve called Fine, while particle sizes retained on 2.36mm sieve size are coarse aggregates and particles retained on 2.36mm sieve 0.075 sieve become mineral fillers (White et al. 2001).

One of the most striking features of aggregate is that their shapes vary enormously from one place to another for design purposes. For instance, some specific types that are suitable for use as a base course may not be satisfactory for surface course of asphalt pavement used in this study. According to Lavin (2003) the aggregate skeletons can be crushed stone, gravel, and sand. Crushed stone produced in boulders or crushed rocks. In the same way, Gravel is also crushed, which can be accommodated in base course. Also, sand is produced either from erosion of bedrock or mechanically crushed. Likewise, sand is notable by its size, the particle sizes are less than 4.75mm and greater than 0.075 mm. It has been outlined that the physical properties of aggregates are plentiful which are of significant role in asphalt design. The most important properties are as follows:

- Shape
- Grading (size)
- Toughness
- Surface texture
- Cleanliness (deleterious materials)
- Adhesion
- Skid resistance
- Durability
- Absorption.

It is vital to identify the potential effects of aggregate gradation and particle shape/texture on permanent deformation of HMA pavements. This is particularly important in locations where rutting tends to form. The problem is that, if one of the above properties of aggregate associated with permanent deformation is not exist, then it is certain that some permanent will be present. Perhaps the aggregate itself is pretty uniform in terms of gradation and other properties but the some properties still missing and the aggregate certainly is not used for the right layer and loading condition. For example, aggregate angularity is very significant in increasing the stability of mixtures. Furthermore, the quality and amount of filler could influence the asphalt performance. On the other hand, rounded fine aggregate particles represented by natural sands produce lower stabilities than crushed fine aggregate particles. In other words, uncrushed aggregates particles such as sands and gravels lead mixtures to poorer stabilities and reduce mixture resistance (Ahlrich 1996).

B.3 Modifier

Modifiers or more precisely polymers can be added to binder in blending process at a certain temperature, depending to the type and the main characteristic of the polymer within the binder. For example, the desired polymer (SBS) in this project to design asphalt mixture was illustrated in detail in literature review (section 2.5.1). Different polymers perform diverse behavior to binder and overall asphalt mixtures, which mean a particular type of polymer, may perform better at higher temperatures. In general, the design of the mixture demands a particular type of polymer to be reasonably survivable.

Appendix C: Detailed Test Procedures

C.1 Detailed Procedures for Multiple Stress Creep Recovery Test (MSCRT)

1. Within the sample preparation stage, the temperature is controlled inside small tins to gain the desired temperature for each sample. Additionally, in case of earlier DSR testing for binder samples, it is necessary to give a rest to the sample to be unloaded (at least one minute) before performing the test.
2. The DSR equipment is calibrated one day before the test including using 25mm lower plate for high temperatures. Also ensuring the level of water inside the circulation tank below the equipment.
3. Inputting the main parameters to the software such as:
   - Temperature
   - Stress levels (which in this test eleven stress levels have been used)
   - Loading time (one second loading followed by 9 seconds rest).
4. Zero gaping is applied for the machine, and leaving the machine to reach the desired temperature.
5. Pouring the sufficient binder on the base plate using hot process.
6. Lowering the spindle to create ca gap of 1.5mm, then trimming the excessive binder around the spindle.
7. Lowering the spindle again to provide the desired gap (1mm).
8. Waiting 15 minutes prior to the test for 'thermal equilibrium', then start the test.
9. As it is commanded, the torque per creep cycle should be fully attained within 0.003 seconds from the beginning of the creep cycle as specialised by the manufacturer.
10. In case of the equipment was unable to record the strain at 1 and 10 seconds, the equipment software will extrapolate earlier data in order to find the strain at the desired time. The data contains a measured data point not exceeding 0.05 second earlier to the desired time for a creep cycle, not exceeding 0.30 second earlier to the desired time for a cycle of recovery.
11. If no rest time is allowed between cycles, it is necessary to repeat the creep and recovery cycle in nine times for the entire ten cycles.
12. The necessary time to finish the two step creep and recovery test is 200 seconds.
13. For each of the twenty cycles the following points were recorded:

- Initial strain rate at the beginning, per cycle, which is symbolised as ϵ_0 and also strain rate at the end of the creep portion which is after 1.0 second of any cycle symbolised as ϵ_c.
- The adjusted strain value after recovery portion (10.0 sec) per each cycle $\epsilon_{10} = \epsilon_r - \epsilon_0$

14. From the results obtained above, average percent recovery and non-recoverable creep compliance can be determined at creep stress levels of 0.100 kPa, 3.200 kPa and 6.4 kPa as below. From the ten cycles at a creep stress of 0.100 kPa determine the percent recovery, ϵ_r (100, N), for N = 1 to 10:

$$\epsilon_r\,(100, \mathrm{N}) = \left(\frac{\epsilon_1 - \epsilon_{10}}{\epsilon_1}\right) * 100$$

15. The percent recovery For each of the ten cycles is determined at a creep stress of 3.200 kPa, ϵ_r(3200, N), for N = 1 to 10:

$$\epsilon_r\,(3200, \mathrm{N}) = \left(\frac{\epsilon_1 - \epsilon_{10}}{\epsilon_1}\right) * 100$$

16. Mean value of percent recovery is determined at 0.100 kPa:

R_{100}= SUM (ϵ_r (100, N))/10 for N= 1 to 10

17. Mean value of percent recovery is determined at 3.200 kPa:

R_{3200}= SUM (ϵ_r (3200, N))/10 for N=1 to 10

18. Percent difference in recovery is determined between 0.100 kPa and 3.200 kPa:

R_{diff} = ((R100-R3200) x100)/ (R100)

19. Non-recoverable compliance, $J_{nr}(100,N)$, for N=1 to 10 is determined for any of the ten cycles at a stress of 0.100 kPa:

J_{nr} (100, N) = $\epsilon_{10}/100$

20. Non-recoverable compliance, $J_{nr}(3200,N)$, for N=1 to 10 is determined for any of the ten cycles at a stress of 3.200 kPa:

J_{nr} (3200, N) = $\epsilon_{10}/3200$

21. Mean value of non-recoverable creep compliance is determined at 0.100 kPa:

J_{nr} 100= SUM (J_{nr} (100, N))/10 for N= 1 to 10

22. Similarly, Mean value of non-recoverable creep compliance is determined at 3.200 kPa:

J_{nr} 3200= SUM (J_{nr} (3200, N))/10 for N=1 to 10

23. Finally, percent difference in non-recoverable creep compliance is determined between 0.100 kPa and 3.200 kPa:

$J_{nr-diff}$ = ((J_{nr}3200 - J_{nr}100) x100)/ (J_{nr}100)

C.2 Detailed Procedure for Wheel Tracking Test (WTT)

1. The specimens should be conditioned for 4 to 16 hours at the specified test temperature, closely prior to WTT, ensuring that the slabs have attained the test temperature ±1.0°C. This test was typically undertaken at a temperature of either 45°C to 60°C, and it was preferred to use 60°C in this project.

Figure C.1: Conditioning the slabs in WTT

2. The WT rut rate was counted in millimetres per hour, at which the deformation increases with time under repeated load passes of the wheel, particularly at the last third period of WTT (last 15 minutes).
3. Controlling temperature is significant, at which the temperature of the specimen is uniform when the test performs. This must be maintained as constant at the specified test temperature ±1.0°C. Therefore, it is preferred to monitor the temperature at intervals of 1 minute or less during the test.
4. The slab should be drilled, to create a small hole to access the temperature monitoring device.

5. It is better to mark each specimen to indicate the direction of wheel flow.
6. It is important to prepare a flat surface of the slabs for the wheel to accelerate smoothly, and a parallel surface to obtain a reasonably stable support underneath. It is also important to certify that there is no adhering material under the tyre of the WT equipment. In other word, the tyre with such materials may affect the outcome of the test. If the surface was sticky, it is recommended to lightly dust it with Talc or French chalk to

C.3 Detailed Procedure for Indirect Tensile Stiffness Modulus Test (ITSMT)

1. The test specimens can be manufactured in different diameters ranging between 100 mm and 150 mm, and different thicknesses between 30mm and 80mm.
2. The ITSMT is considered to be partially destructive; therefore it is crucial to provide a resting period of time between tests, especially when RLAT is undertaken subsequently. Specifically, at which the required time is one day to gain a full recovery.
3. Re-test is required if stiffness modulus in second orientation is greater than 10% difference.
4. In case of stiffness modulus in second orientation 20% lower, or 10% higher than first orientation, this is not possible and rejecting result is recommended when no re-testing is preferred.

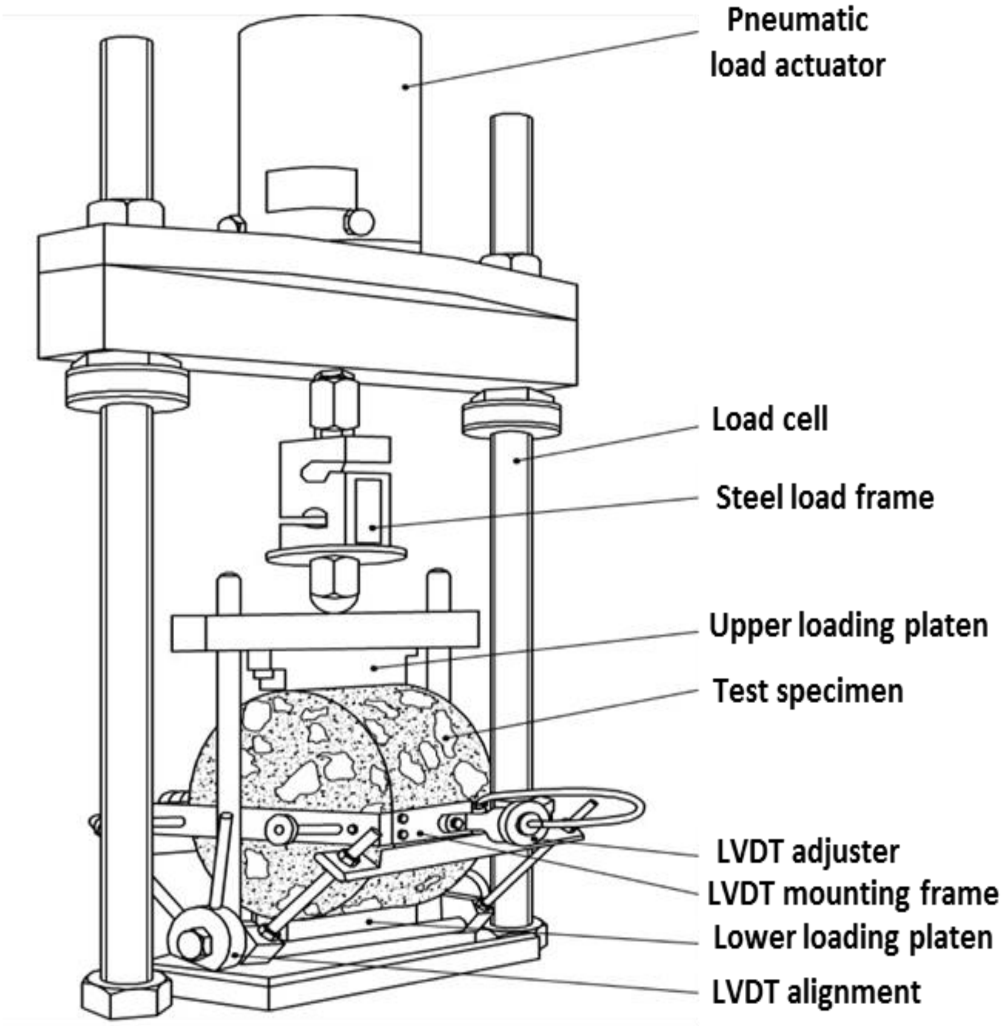


Figure C.2 ITSMT equipment configuration

5. Determination of the specimen thickness and diameter are of great importance, in which the defined outcomes by the instrument relay on these dimensions.
6. The mean value of the thicknesses and diameters are determined (Table C.1 and Table C.2) by taking measurements for the specimen thickness from the four quarters of the sample. Meanwhile, six measurements are taken, three from each half by marking, prior to the measurements.

Table C.1: Determination of the specimen 'Thickness' for ITSMT and RLAT

Specimen No.	**First Thickness (mm)**	**Second Thickness (mm)**	**Third Thickness (mm)**	**Forth Thickness (mm)**	**Mean value (mm)**
14-1384	40.5	41	41.3	40.5	**40.8**
14-1385	41	41.1	41.2	41.1	**41.1**
14-1386	40.2	40.5	38.9	39	**39.7**
14-1387	40.1	39.8	41	40.6	**40.4**
14-1388	38.8	39.2	39.8	39.2	**39.3**
14-1389	39.9	40.1	39.7	39.6	**39.8**
14-1390	41.5	41.6	41	41	**41.3**
14-1391	40.2	41.5	40.6	39.8	**40.5**
14-1392	40.5	40.3	41.1	41.1	**40.8**
14-1393	40.1	40.5	40.4	40	**40.3**
14-1394	41.4	41.8	41	41.5	**41.4**
14-1395	41.4	41.6	41.2	41	**41.3**
14-1396	40.2	41.2	41.2	40.8	**40.9**
14-1397	41.6	41.2	41.4	41.3	**41.4**
14-1398	41.2	41.1	40.7	41.1	**41.0**
14-1399	40.9	41.4	41	41.1	**41.1**
14-1400	40.8	41.1	41.4	41.8	**41.3**
14-1401	41.2	41.7	42.5	41.9	**41.8**

Table C.2: Determination of the specimen 'Diameter' for ITSMT and RLAT

Specimen No.	First Thickness (mm)	Second Thickness (mm)	Third Thickness (mm)	Forth Thickness (mm)	Fifth Thickness (mm)	Sixth Thickness (mm)	Mean value (mm)
14-1384	99.4	99.3	99	99.3	99.3	99.3	**99.3**
14-1385	99.4	99.1	98.8	99.3	98.6	98.7	**99.0**
14-1386	99.1	99	99.2	99.3	99.4	99.2	**99.2**
14-1387	99.3	99.3	99.2	99.4	99.4	99.2	**99.3**
14-1388	99.4	99.3	99.1	99.3	99.3	99.2	**99.3**
14-1389	99.3	99.3	98.6	99.4	99.1	99.3	**99.2**
14-1390	99.2	99.4	99.3	99.1	99.0	98.8	**99.1**
14-1391	99	99.1	99	99.3	99.3	99.1	**99.1**
14-1392	99.2	99.3	99.2	99	99.1	99.1	**99.2**
14-1393	99.2	99.5	99.2	99.2	99.4	99.4	**99.3**
14-1394	99.4	99.3	99.4	99.3	99.4	99.3	**99.4**
14-1395	99.3	99.4	99.3	99.4	99.4	99.3	**99.4**
14-1396	99.5	99.4	99	99.5	99.4	98.7	**99.3**
14-1397	99.4	99.4	99	99.4	99.4	99.1	**99.3**
14-1398	99.4	99.4	99.3	99.4	98.7	99.2	**99.2**
14-1399	99.3	99.4	99.3	99.2	98.8	98.8	**99.1**
14-1400	99.3	99.3	99	99.2	98.8	99	**99.1**
14-1401	99.4	99.3	99.3	99.2	99.0	99	**99.2**

C.4 Detailed Procedure for Repeated Load Axial Test (RLAT)

1. The mean value of the thickness and the diameter measurements sorted within each of the two above tables, were used in the RLAT as an input parameter.
2. The RLAT is performed using a cylindrical specimen with a diameter ranging between 100mm or 150mm and thickness preferably between 40mm and 100mm.
3. The specimens are conditioned to certify that the loading plates are appropriately placed on the sample prior to running the test.
4. Specifically, the samples undergo conditioning process with applying a static stress of 10 kPa for ten minutes. After the initial stress, a 100kPa axial stress is applied in 1 second square wave pulses with 1 second rest periods. This simulates the slow moving traffic, which consequently leads to the most of the deformations on roadways.
5. The test is repeated for 1800 load cycles at 30 °C or 40 °C lasting a period of 1800 seconds. The test is stopped, if the deformation of a specimen is more than 8 mm before reaching the specified number of pulses.
6. The test lasts until either 8 mm deformation or the desired number of cycles, which are 1800 or 3600 cycles.
7. In case of a specimen deformation greater than 8 mm prior reaching the stated number of pulses, the test is then terminated.
8. The test outcome should consist of percentage of axial strain of the specimen plotted against number of load cycles.

Appendix D: Test Results

D.1 Multiple Stress Creep Recovery Test (MSCRT)

Table D.1: Recovery of Pen binder at temperature 50°C

Pen 40/60									
Description	**% RECOVERY**								
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	8.099	8.697	9.711	10.420	10.100	9.392	6.854	3.705	1.577
2	9.030	10.437	10.738	10.709	10.537	8.895	6.738	3.717	2.146
3	8.733	9.743	10.389	9.895	9.760	9.042	6.996	3.671	2.117
4	9.858	9.180	9.993	10.503	10.362	9.271	7.070	3.713	2.023
5	8.943	9.248	10.921	10.944	10.314	9.524	6.866	3.825	2.060
6	10.605	10.063	10.448	10.181	9.976	9.140	6.768	3.852	2.149
7	8.314	9.480	10.127	10.314	10.389	8.903	6.987	3.879	2.043
8	9.535	10.701	10.811	10.960	10.152	9.066	6.987	3.867	1.934
9	9.402	9.901	10.448	10.203	10.151	9.353	6.792	3.768	1.929
10	8.963	10.168	10.074	10.201	10.291	9.425	6.765	3.730	1.983
AVERAGE	**9.148**	**9.762**	**10.366**	**10.433**	**10.203**	**9.201**	**6.882**	**3.773**	**1.996**
Min.	**8.099**	**8.697**	**9.711**	**9.895**	**9.760**	**8.895**	**6.738**	**3.671**	**1.577**
Max.	**10.605**	**10.701**	**10.921**	**10.960**	**10.537**	**9.524**	**7.070**	**3.879**	**2.149**
Standard dev.	**0.738**	**0.617**	**0.390**	**0.349**	**0.225**	**0.223**	**0.119**	**0.076**	**0.167**
Differences between 0.1 kPa & 3.20 kPa	**5.7**								
Differences between 0.1 kPa & 6.40kPa	**29.5**								

Table D.2: Non-recoverable of Pen binder at temperature 50°C

Pen 40/60									
Description	**NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})**								
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 KPa**	**12.8 KPa**	**25.6 KPa**
1	0.320	0.308	0.305	0.310	0.309	0.317	0.327	0.343	0.488
2	0.324	0.295	0.299	0.302	0.310	0.317	0.327	0.342	0.362
3	0.320	0.296	0.317	0.311	0.312	0.314	0.326	0.342	0.367
4	0.318	0.298	0.306	0.309	0.310	0.315	0.327	0.344	0.373
5	0.324	0.305	0.300	0.303	0.312	0.315	0.326	0.344	0.371
6	0.322	0.313	0.315	0.310	0.309	0.317	0.327	0.343	0.377
7	0.320	0.313	0.302	0.311	0.309	0.317	0.327	0.343	0.390
8	0.315	0.315	0.297	0.303	0.314	0.317	0.327	0.344	0.396
9	0.312	0.319	0.315	0.309	0.308	0.315	0.326	0.345	0.397
10	0.311	0.315	0.306	0.313	0.312	0.315	0.327	0.345	0.405
AVERAGE	**0.319**	**0.308**	**0.306**	**0.308**	**0.310**	**0.316**	**0.327**	**0.344**	**0.393**
min	**0.297**	**0.295**	**0.297**	**0.302**	**0.308**	**0.314**	**0.326**	**0.342**	**0.362**
max	**0.324**	**0.319**	**0.317**	**0.313**	**0.314**	**0.317**	**0.327**	**0.345**	**0.488**
Standard dev.	**0.005**	**0.009**	**0.007**	**0.004**	**0.002**	**0.001**	**0.000**	**0.001**	**0.036**
Differences between 0.1 kPa & 3.20 kPa	**2.6**								
Differences between 0.1 kPa & 6.40kPa	**6.2**								

Table D.3: Recovery of 3% PMB at temperature 50°C

3% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	32.785	36.667	35.706	36.679	38.426	36.397	35.866	31.815	0.902
2	39.008	39.121	37.713	37.188	37.591	38.690	35.327	32.071	1.293
3	39.099	38.073	37.827	38.431	37.383	36.302	35.783	31.766	2.326
4	35.974	38.791	38.451	39.139	39.837	37.988	36.584	31.583	4.341
5	36.723	38.119	38.474	39.185	38.578	38.003	35.454	32.319	14.791
6	34.843	39.606	39.005	38.603	37.227	36.985	35.400	32.297	15.569
7	36.632	36.614	38.814	38.626	39.484	38.617	36.110	32.055	12.468
8	35.916	38.469	38.672	38.125	39.596	36.769	35.912	32.004	15.259
9	38.724	37.361	39.002	38.422	38.039	38.556	35.434	32.418	15.578
10	39.603	37.972	38.585	39.119	38.520	37.925	35.566	32.226	22.231
AVERAGE	**36.931**	**38.079**	**38.225**	**38.352**	**38.468**	**37.623**	**35.744**	**32.055**	**10.476**
Min.	**32.785**	**36.614**	**35.706**	**36.679**	**37.227**	**36.302**	**35.327**	**31.583**	**0.902**
Max.	**39.603**	**39.606**	**39.005**	**39.185**	**39.837**	**38.690**	**36.584**	**32.418**	**22.231**
Standard dev.	**2.186**	**0.986**	**0.987**	**0.834**	**0.935**	**0.928**	**0.393**	**0.270**	**7.570**
Differences between 0.1 kPa & 3.20 kPa	**1.2**								
Differences between 0.1 kPa & 6.40kPa	**6.1**								

Table D.4: Non-recoverable of 3% PMB at temperature 50°C

3% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.077	0.070	0.068	0.070	0.068	0.070	0.072	0.078	2.748
2	0.068	0.067	0.065	0.067	0.070	0.068	0.072	0.078	2.386
3	0.069	0.069	0.065	0.065	0.067	0.071	0.072	0.078	1.263
4	0.071	0.067	0.066	0.065	0.065	0.069	0.071	0.078	0.697
5	0.071	0.068	0.067	0.067	0.069	0.068	0.072	0.077	0.184
6	0.074	0.066	0.067	0.069	0.068	0.070	0.072	0.077	0.172
7	0.071	0.068	0.068	0.068	0.065	0.068	0.072	0.078	0.231
8	0.072	0.068	0.069	0.068	0.067	0.070	0.072	0.078	0.184
9	0.068	0.067	0.068	0.065	0.069	0.069	0.073	0.078	0.181
10	0.067	0.068	0.069	0.064	0.066	0.069	0.073	0.078	0.118
AVERAGE	**0.071**	**0.068**	**0.067**	**0.067**	**0.067**	**0.069**	**0.072**	**0.078**	**0.816**
Min.	**0.065**	**0.066**	**0.065**	**0.064**	**0.065**	**0.068**	**0.071**	**0.077**	**0.118**
Max.	**0.077**	**0.070**	**0.069**	**0.070**	**0.070**	**0.071**	**0.073**	**0.078**	**2.748**
Standard dev.	**0.003**	**0.001**	**0.002**	**0.002**	**0.002**	**0.001**	**0.000**	**0.000**	**0.992**
Differences between 0.1 kPa & 3.20 kPa	**2.0**								
Differences between 0.1 kPa & 6.40kPa	**6.4**								

Table D.5: Recovery of 5% PMB at temperature 50°C

5% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	70.497	83.018	82.341	86.108	86.590	85.827	85.976	82.972	-2.321
2	73.856	86.382	86.672	88.667	88.928	88.139	88.006	85.245	0.063
3	78.920	85.959	87.213	89.814	90.238	89.081	88.660	87.348	84.666
4	78.213	86.258	88.544	90.408	90.848	89.779	89.073	85.133	85.419
5	76.198	87.491	89.623	90.915	91.044	90.473	89.667	87.832	86.345
6	83.571	88.913	90.307	91.648	91.634	90.791	90.053	86.174	86.915
7	85.003	89.655	90.757	91.599	91.717	91.238	90.461	88.948	86.814
8	86.206	89.657	90.262	92.268	92.134	91.496	90.854	88.694	87.545
9	79.734	89.972	90.516	92.135	92.469	91.934	91.256	86.886	87.753
10	80.531	89.445	92.317	92.596	92.592	92.176	91.450	89.660	87.672
AVERAGE	**79.273**	**87.675**	**88.855**	**90.616**	**90.819**	**90.093**	**89.546**	**86.889**	**69.087**
Min.	**70.497**	**83.018**	**82.341**	**86.108**	**86.590**	**85.827**	**85.976**	**82.972**	**-2.321**
Max.	**86.206**	**89.972**	**92.317**	**92.596**	**92.592**	**92.176**	**91.450**	**89.660**	**87.753**
Standard dev.	**4.924**	**2.264**	**2.849**	**1.997**	**1.853**	**1.966**	**1.683**	**2.052**	**37.025**
Differences between 0.1 kPa & 3.20 kPa	**-2.8**								
Differences between 0.1 kPa & 6.40kPa	**-2.1**								

Table D.6: Non-recoverable of 5% PMB at temperature 50°C

5% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1.000	0.018	0.010	0.011	0.009	0.009	0.009	0.009	0.012	173.906
2.000	0.016	0.008	0.008	0.007	0.007	0.008	0.008	0.010	124.570
3.000	0.013	0.009	0.008	0.006	0.006	0.007	0.007	0.008	0.011
4.000	0.013	0.008	0.007	0.006	0.006	0.007	0.007	0.010	0.010
5.000	0.015	0.008	0.006	0.006	0.006	0.006	0.007	0.008	0.010
6.000	0.010	0.007	0.006	0.005	0.006	0.006	0.006	0.009	0.009
7.000	0.009	0.006	0.006	0.005	0.005	0.006	0.006	0.007	0.009
8.000	0.008	0.006	0.006	0.005	0.005	0.005	0.006	0.008	0.009
9.000	0.013	0.006	0.006	0.005	0.005	0.005	0.006	0.009	0.008
10.000	0.012	0.006	0.005	0.005	0.005	0.005	0.006	0.007	0.009
AVERAGE	**0.013**	**0.007**	**0.007**	**0.006**	**0.006**	**0.006**	**0.007**	**0.009**	**29.855**
Min.	**0.005**	**0.006**	**0.005**	**0.005**	**0.005**	**0.005**	**0.006**	**0.007**	**0.008**
Max.	**0.018**	**0.010**	**0.011**	**0.009**	**0.009**	**0.009**	**0.009**	**0.012**	**173.906**
Standard dev.	**0.003**	**0.001**	**0.002**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**63.986**
Differences between 0.1 kPa & 3.20 kPa	**-14.8**								
Differences between 0.1 kPa & 6.40kPa	**-8.7**								

Table D.7: Recovery of 7% PMB at temperature 50°C

7% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1.000	83.446	96.794	86.355	88.238	87.774	87.550	87.660	86.138	3.448
2.000	87.998	98.789	87.457	89.800	89.480	89.471	89.740	88.571	10.981
3.000	105.266	97.537	90.990	89.687	90.417	89.975	90.647	89.713	29.951
4.000	91.756	92.946	90.891	90.673	91.230	90.569	91.118	90.120	48.347
5.000	100.437	96.082	91.887	91.326	91.389	91.171	91.319	90.628	13.423
6.000	95.658	92.903	91.550	92.129	91.824	91.216	91.497	89.696	14.339
7.000	99.337	100.020	92.494	92.336	92.186	91.722	91.585	90.714	8.417
8.000	84.672	97.696	94.048	92.291	92.779	92.011	91.717	90.708	35.814
9.000	103.643	94.725	93.663	93.011	92.571	92.328	91.853	89.689	20.823
10.000	90.152	93.888	93.692	92.151	92.637	92.277	91.817	89.298	15.667
AVERAGE	**94.237**	**96.138**	**91.302**	**91.164**	**91.229**	**90.829**	**90.895**	**89.527**	**20.121**
Min.	**83.446**	**92.903**	**86.355**	**88.238**	**87.774**	**87.550**	**87.660**	**86.138**	**3.448**
Max.	**105.266**	**100.020**	**94.048**	**93.011**	**92.779**	**92.328**	**91.853**	**90.714**	**48.347**
Standard dev.	**7.791**	**2.464**	**2.586**	**1.521**	**1.603**	**1.498**	**1.307**	**1.371**	**13.891**
Differences between 0.1 kPa & 3.20 kPa	**5.5**								
Differences between 0.1 kPa & 6.40kPa	**5.5**								

Table D.8: Non-recoverable of 7% PMB at temperature 50°C

7% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1.000	0.007	0.001	0.005	0.005	0.005	0.005	0.005	0.005	0.963
2.000	0.005	0.000	0.005	0.004	0.004	0.004	0.004	0.004	0.284
3.000	-0.002	0.001	0.003	0.004	0.004	0.004	0.004	0.004	0.083
4.000	0.003	0.003	0.003	0.004	0.003	0.003	0.003	0.004	0.038
5.000	0.000	0.001	0.003	0.003	0.003	0.003	0.003	0.004	0.230
6.000	0.002	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.214
7.000	0.000	0.000	0.003	0.003	0.003	0.003	0.003	0.004	0.391
8.000	0.006	0.001	0.002	0.003	0.003	0.003	0.003	0.004	0.065
9.000	-0.001	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.138
10.000	0.004	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.194
AVERAGE	**0.002**	**0.001**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.004**	**0.260**
Min.	**0.002**	**0.000**	**0.002**	**0.003**	**0.003**	**0.003**	**0.003**	**0.004**	**0.038**
Max.	**0.007**	**0.003**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.005**	**0.963**
Standard dev.	**0.003**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.000**	**0.001**	**0.269**
Differences between 0.1 kPa & 3.20 kPa	**134.7**								
Differences between 0.1 kPa & 6.40kPa	**142.6**								

Table D.9: Recovery of Pen binder at temperature 60°C

Pen 40/60									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	1.942	3.211	3.629	3.302	2.764	1.635	0.989	0.411	0
2	1.791	3.077	3.652	3.234	2.644	1.612	0.939	0.435	0
3	1.821	3.432	3.524	3.223	2.764	1.686	0.910	0.484	0
4	2.552	3.167	3.831	3.475	2.838	1.662	0.950	0.480	0
5	2.407	3.350	3.471	3.478	2.591	1.701	0.951	0.479	0
6	2.260	3.432	3.584	3.472	2.800	1.621	0.930	0.429	0
7	2.062	3.230	3.445	3.472	2.720	1.645	0.951	0.427	0
8	1.956	3.347	3.673	3.299	2.773	1.685	0.941	0.423	0
9	2.678	3.215	3.545	3.311	2.857	1.682	0.962	0.422	0
10	2.319	3.274	3.547	3.229	2.694	1.723	0.973	0.467	0
AVERAGE	**2.179**	**3.273**	**3.590**	**3.349**	**2.744**	**1.665**	**0.950**	**0.446**	**0**
Min.	**1.791**	**3.077**	**3.445**	**3.223**	**2.591**	**1.612**	**0.910**	**0.411**	**0**
Max.	**2.678**	**3.432**	**3.831**	**3.478**	**2.857**	**1.723**	**0.989**	**0.484**	**0**
Standard dev.	**0.310**	**0.116**	**0.112**	**0.112**	**0.084**	**0.036**	**0.022**	**0.028**	**0**
Differences between 0.1 kPa & 3.20 kPa	**49.1**								
Differences between 0.1 kPa & 6.40kPa	**71.0**								

Table D.10: Non-recoverable of Pen binder at temperature 60°C

Pen 40/60									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	1.464	1.447	1.414	1.428	1.451	1.485	1.549	1.894	0.000
2	1.469	1.386	1.398	1.421	1.450	1.488	1.549	1.610	0.000
3	1.412	1.407	1.417	1.426	1.451	1.494	1.548	1.607	0.000
4	1.367	1.437	1.393	1.424	1.455	1.498	1.548	1.619	0.000
5	1.427	1.356	1.418	1.423	1.457	1.499	1.546	1.623	0.000
6	1.470	1.435	1.413	1.425	1.454	1.498	1.547	1.630	0.000
7	1.463	1.408	1.416	1.425	1.453	1.495	1.545	1.638	0.000
8	1.413	1.386	1.416	1.429	1.446	1.495	1.546	1.657	0.000
9	1.352	1.445	1.408	1.424	1.445	1.498	1.544	1.660	0.000
10	1.407	1.359	1.428	1.424	1.445	1.497	1.542	1.666	0.000
AVERAGE	**1.425**	**1.407**	**1.412**	**1.425**	**1.451**	**1.495**	**1.546**	**1.661**	**0.000**
Min.	**1.393**	**1.356**	**1.393**	**1.421**	**1.445**	**1.485**	**1.542**	**1.607**	**0.000**
Max.	**1.470**	**1.447**	**1.428**	**1.429**	**1.457**	**1.499**	**1.549**	**1.894**	**0.000**
Standard dev.	**0.043**	**0.034**	**0.010**	**0.002**	**0.004**	**0.005**	**0.002**	**0.085**	**0.000**
Differences between 0.1 kPa & 3.20 kPa		**6.3**							
Differences between 0.1 kPa & 6.40kPa		**9.9**							

Table D.11: Recovery of 3% PMB at temperature 60°C

3% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	13.489	15.273	15.082	16.929	15.841	13.283	9.858	6.693	0.264
2	13.868	15.175	16.771	16.741	15.797	13.460	9.864	6.845	3.625
3	14.636	15.726	15.856	16.470	15.394	13.094	9.819	6.798	2.039
4	14.608	15.599	16.762	15.969	16.137	13.238	9.919	6.848	2.405
5	14.815	15.879	16.821	16.549	15.697	13.270	9.916	6.868	2.695
6	15.113	16.794	16.091	17.369	15.361	13.234	9.829	6.891	3.264
7	14.869	16.244	17.401	17.308	15.955	13.428	9.867	6.878	2.894
8	14.405	16.401	16.338	16.983	15.485	13.234	9.897	6.807	2.947
9	14.760	16.452	17.356	16.157	15.196	13.544	9.861	6.827	4.006
10	15.281	16.213	17.097	16.610	16.269	13.067	9.910	6.879	4.050
AVERAGE	**14.584**	**15.976**	**16.557**	**16.709**	**15.713**	**13.285**	**9.874**	**6.833**	**2.819**
Min.	**13.489**	**15.175**	**15.082**	**15.969**	**15.196**	**13.067**	**9.819**	**6.693**	**0.264**
Max.	**15.281**	**16.794**	**17.401**	**17.369**	**16.269**	**13.544**	**9.919**	**6.891**	**4.050**
Standard dev.	**0.545**	**0.533**	**0.725**	**0.455**	**0.352**	**0.153**	**0.035**	**0.058**	**1.112**
Differences between 0.1 kPa & 3.20 kPa	**16.8**								
Differences between 0.1 kPa & 6.40kPa	**38.2**								

Table D.12: Non-recoverable of 3% PMB at temperature 60°C

3% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.369	0.390	0.377	0.370	0.375	0.398	0.436	0.494	11.809
2	0.371	0.389	0.367	0.373	0.374	0.398	0.435	0.495	0.779
3	0.376	0.378	0.385	0.372	0.378	0.400	0.435	0.497	1.408
4	0.379	0.369	0.364	0.376	0.376	0.399	0.436	0.497	1.189
5	0.382	0.361	0.381	0.370	0.379	0.400	0.437	0.499	1.072
6	0.384	0.360	0.370	0.368	0.381	0.402	0.436	0.500	0.903
7	0.384	0.370	0.366	0.368	0.379	0.401	0.435	0.501	1.009
8	0.390	0.378	0.382	0.367	0.381	0.402	0.438	0.503	0.978
9	0.390	0.383	0.360	0.374	0.382	0.401	0.437	0.505	0.711
10	0.391	0.385	0.377	0.368	0.377	0.401	0.436	0.507	0.713
AVERAGE	**0.382**	**0.376**	**0.373**	**0.370**	**0.378**	**0.400**	**0.436**	**0.500**	**2.057**
Min.	**0.360**	**0.360**	**0.360**	**0.367**	**0.374**	**0.398**	**0.435**	**0.494**	**0.711**
Max.	**0.391**	**0.390**	**0.385**	**0.376**	**0.382**	**0.402**	**0.438**	**0.507**	**11.809**
Standard dev.	**0.008**	**0.011**	**0.009**	**0.003**	**0.003**	**0.001**	**0.001**	**0.004**	**3.433**
Differences between 0.1 kPa & 3.20 kPa	**6.4**								
Differences between 0.1 kPa & 6.40kPa	**15.9**								

Table D.13: Recovery of 5% PMB at temperature 60°C

5% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	69.496	76.780	74.559	77.739	77.071	75.809	73.443	69.588	0.713
2	77.014	80.846	78.674	80.742	79.598	79.142	75.996	71.400	6.770
3	80.700	80.631	80.568	82.393	80.865	79.683	76.845	72.042	12.791
4	81.233	82.778	81.746	83.520	82.143	79.861	76.938	72.866	31.833
5	81.329	83.907	82.456	84.354	83.268	80.815	77.948	73.265	43.369
6	81.306	83.403	83.572	84.540	84.076	81.840	77.928	73.351	57.349
7	84.222	85.676	83.978	84.980	84.171	81.530	77.938	73.882	7.929
8	84.216	85.074	84.484	85.204	83.970	81.156	78.727	73.860	41.698
9	82.597	84.623	84.594	85.351	83.932	81.589	78.031	74.184	28.914
10	82.882	85.715	84.843	85.380	83.813	82.541	78.654	74.719	19.238
AVERAGE	**80.500**	**82.943**	**81.947**	**83.420**	**82.291**	**80.397**	**77.245**	**72.916**	**25.060**
Min.	**69.496**	**76.780**	**74.559**	**77.739**	**77.071**	**75.809**	**73.443**	**69.588**	**0.713**
Max.	**84.222**	**85.715**	**84.843**	**85.380**	**84.171**	**82.541**	**78.727**	**74.719**	**57.349**
Standard dev.	**4.383**	**2.817**	**3.267**	**2.491**	**2.405**	**1.931**	**1.581**	**1.532**	**18.620**
Differences between 0.1 kPa & 3.20 kPa	**3.1**								
Differences between 0.1 kPa & 6.40kPa	**6.9**								

Table D.14: Non-recoverable of 5% PMB at temperature 60°C

5% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.049	0.037	0.040	0.033	0.036	0.038	0.043	0.052	17.941
2	0.036	0.030	0.034	0.029	0.031	0.032	0.039	0.050	1.850
3	0.030	0.030	0.030	0.026	0.029	0.032	0.037	0.049	0.951
4	0.029	0.027	0.028	0.025	0.027	0.032	0.037	0.047	0.306
5	0.029	0.025	0.027	0.024	0.025	0.030	0.036	0.047	0.191
6	0.029	0.026	0.025	0.024	0.025	0.028	0.036	0.047	0.111
7	0.025	0.022	0.024	0.023	0.025	0.029	0.036	0.046	1.742
8	0.024	0.023	0.024	0.023	0.025	0.030	0.034	0.047	0.212
9	0.027	0.024	0.023	0.023	0.025	0.029	0.036	0.046	0.376
10	0.027	0.022	0.023	0.023	0.025	0.027	0.035	0.045	0.646
AVERAGE	**0.031**	**0.027**	**0.028**	**0.025**	**0.027**	**0.031**	**0.037**	**0.048**	**2.433**
Min.	**0.023**	**0.022**	**0.023**	**0.023**	**0.025**	**0.027**	**0.034**	**0.045**	**0.111**
Max.	**0.049**	**0.037**	**0.040**	**0.033**	**0.036**	**0.038**	**0.043**	**0.052**	**17.941**
Standard dev.	**0.007**	**0.005**	**0.006**	**0.003**	**0.004**	**0.003**	**0.002**	**0.002**	**5.486**
Differences between 0.1 kPa & 3.20 kPa	**13.9**								
Differences between 0.1 kPa & 6.40kPa	**37.1**								

Table D.15: Recovery of 7% PMB at temperature 60°C

7% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	34.178	43.053	41.989	45.186	43.817	42.092	41.126	36.199	10.958
2	41.517	44.936	44.925	47.366	45.166	45.715	41.770	36.793	27.891
3	40.344	47.056	46.699	47.902	48.073	44.146	42.220	37.329	12.293
4	44.913	46.847	47.648	48.241	47.833	46.074	42.763	37.593	22.414
5	44.005	48.155	48.052	48.120	46.545	45.993	42.795	37.853	25.661
6	46.345	47.295	48.612	48.368	48.093	45.672	43.067	37.615	26.090
7	45.912	48.733	48.775	49.145	49.456	46.906	42.939	37.669	13.162
8	46.670	50.340	49.276	50.564	48.603	45.140	42.874	37.760	11.122
9	45.932	49.678	49.481	50.578	47.135	47.668	43.684	37.826	2.978
10	46.032	48.976	50.415	50.836	49.144	45.473	43.351	37.764	1.548
AVERAGE	**43.585**	**47.507**	**47.587**	**48.631**	**47.387**	**45.488**	**42.659**	**37.440**	**15.412**
Min.	**34.178**	**43.053**	**41.989**	**45.186**	**43.817**	**42.092**	**41.126**	**36.199**	**1.548**
Max.	**46.670**	**50.340**	**50.415**	**50.836**	**49.456**	**47.668**	**43.684**	**37.853**	**27.891**
Standard dev.	**3.934**	**2.210**	**2.502**	**1.736**	**1.778**	**1.524**	**0.759**	**0.538**	**9.566**
Differences between 0.1 kPa & 3.20 kPa	**4.2**								
Differences between 0.1 kPa & 6.40kPa	**10.2**								

Table D.16: Non-recoverable of 7% PMB at temperature 60°C

7% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.075	0.067	0.071	0.064	0.069	0.070	0.072	0.080	0.315
2	0.070	0.064	0.068	0.064	0.065	0.066	0.071	0.079	0.104
3	0.067	0.062	0.065	0.064	0.061	0.068	0.071	0.079	0.292
4	0.063	0.063	0.064	0.064	0.064	0.065	0.070	0.079	0.144
5	0.064	0.062	0.063	0.063	0.064	0.065	0.070	0.079	0.122
6	0.063	0.063	0.062	0.061	0.060	0.066	0.070	0.079	0.120
7	0.063	0.062	0.061	0.058	0.060	0.065	0.070	0.079	0.280
8	0.063	0.060	0.060	0.057	0.063	0.066	0.070	0.079	0.341
9	0.064	0.061	0.058	0.058	0.063	0.063	0.069	0.080	1.362
10	0.062	0.062	0.057	0.059	0.060	0.066	0.069	0.080	2.558
AVERAGE	**0.065**	**0.063**	**0.063**	**0.061**	**0.063**	**0.066**	**0.070**	**0.080**	**0.564**
Min.	**0.057**	**0.060**	**0.057**	**0.057**	**0.060**	**0.063**	**0.069**	**0.079**	**0.104**
Max.	**0.075**	**0.067**	**0.071**	**0.064**	**0.069**	**0.070**	**0.072**	**0.080**	**2.558**
Standard dev.	**0.004**	**0.002**	**0.004**	**0.003**	**0.003**	**0.002**	**0.001**	**0.001**	**0.793**
Differences between 0.1 kPa & 3.20 kPa	**5.5**								
Differences between 0.1 kPa & 6.40kPa	**12.2**								

Table D.17: Recovery of Pen binder at temperature 60°C (Repeated test)

Pen 40/60									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	1.942	3.211	3.629	3.302	2.764	1.635	0.989	0.411	0
2	1.791	3.077	3.652	3.234	2.644	1.612	0.939	0.435	0
3	1.821	3.432	3.524	3.223	2.764	1.686	0.910	0.484	0
4	2.552	3.167	3.831	3.475	2.838	1.662	0.950	0.480	0
5	2.407	3.350	3.471	3.478	2.591	1.701	0.951	0.479	0
6	2.260	3.432	3.584	3.472	2.800	1.621	0.930	0.429	0
7	2.062	3.230	3.445	3.472	2.720	1.645	0.951	0.427	0
8	1.956	3.347	3.673	3.299	2.773	1.685	0.941	0.423	0
9	2.678	3.215	3.545	3.311	2.857	1.682	0.962	0.422	0
10	2.319	3.274	3.547	3.229	2.694	1.723	0.973	0.467	0
AVERAGE	**2.179**	**3.273**	**3.590**	**3.349**	**2.744**	**1.665**	**0.950**	**0.446**	**0**
Min.	**1.791**	**3.077**	**3.445**	**3.223**	**2.591**	**1.612**	**0.910**	**0.411**	**0**
Max.	**2.678**	**3.432**	**3.831**	**3.478**	**2.857**	**1.723**	**0.989**	**0.484**	**0**
Standard dev.	**0.310**	**0.116**	**0.112**	**0.112**	**0.084**	**0.036**	**0.022**	**0.028**	**0**
Differences between 0.1 kPa & 3.20 kPa	**49.1**								
Differences between 0.1 kPa & 6.40kPa	**71.0**								

Table D.18: Non-recoverable of Pen binder at temperature 60°C (Repeated test)

Pen 40/60									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	1.464	1.447	1.414	1.428	1.451	1.485	1.549	1.894	0.000
2	1.469	1.386	1.398	1.421	1.450	1.488	1.549	1.610	0.000
3	1.412	1.407	1.417	1.426	1.451	1.494	1.548	1.607	0.000
4	1.367	1.437	1.393	1.424	1.455	1.498	1.548	1.619	0.000
5	1.427	1.356	1.418	1.423	1.457	1.499	1.546	1.623	0.000
6	1.470	1.435	1.413	1.425	1.454	1.498	1.547	1.630	0.000
7	1.463	1.408	1.416	1.425	1.453	1.495	1.545	1.638	0.000
8	1.413	1.386	1.416	1.429	1.446	1.495	1.546	1.657	0.000
9	1.352	1.445	1.408	1.424	1.445	1.498	1.544	1.660	0.000
10	1.407	1.359	1.428	1.424	1.445	1.497	1.542	1.666	0.000
AVERAGE	**1.425**	**1.407**	**1.412**	**1.425**	**1.451**	**1.495**	**1.546**	**1.661**	**0.000**
Min.	**1.393**	**1.356**	**1.393**	**1.421**	**1.445**	**1.485**	**1.542**	**1.607**	**0.000**
Max.	**1.470**	**1.447**	**1.428**	**1.429**	**1.457**	**1.499**	**1.549**	**1.894**	**0.000**
Standard dev.	**0.043**	**0.034**	**0.010**	**0.002**	**0.004**	**0.005**	**0.002**	**0.085**	**0.000**
Differences between 0.1 kPa & 3.20 kPa		**6.3**							
Differences between 0.1 kPa & 6.40kPa		**9.9**							

Table D.19: Recovery of 3% PMB at temperature 60°C (Repeated test)

3% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	13.489	15.273	15.082	16.929	15.841	13.283	9.858	6.693	0.264
2	13.868	15.175	16.771	16.741	15.797	13.460	9.864	6.845	3.625
3	14.636	15.726	15.856	16.470	15.394	13.094	9.819	6.798	2.039
4	14.608	15.599	16.762	15.969	16.137	13.238	9.919	6.848	2.405
5	14.815	15.879	16.821	16.549	15.697	13.270	9.916	6.868	2.695
6	15.113	16.794	16.091	17.369	15.361	13.234	9.829	6.891	3.264
7	14.869	16.244	17.401	17.308	15.955	13.428	9.867	6.878	2.894
8	14.405	16.401	16.338	16.983	15.485	13.234	9.897	6.807	2.947
9	14.760	16.452	17.356	16.157	15.196	13.544	9.861	6.827	4.006
10	15.281	16.213	17.097	16.610	16.269	13.067	9.910	6.879	4.050
AVERAGE	**14.584**	**15.976**	**16.557**	**16.709**	**15.713**	**13.285**	**9.874**	**6.833**	**2.819**
Min.	**13.489**	**15.175**	**15.082**	**15.969**	**15.196**	**13.067**	**9.819**	**6.693**	**0.264**
Max.	**15.281**	**16.794**	**17.401**	**17.369**	**16.269**	**13.544**	**9.919**	**6.891**	**4.050**
Standard dev.	**0.545**	**0.533**	**0.725**	**0.455**	**0.352**	**0.153**	**0.035**	**0.058**	**1.112**
Differences between 0.1 kPa & 3.20 kPa	**16.8**								
Differences between 0.1 kPa & 6.40kPa	**38.2**								

Table D.20: Non-recoverable of 3% PMB at temperature 60°C (Repeated test)

3% SBS PMB									
NON RECOVERABLE CREEP COMPLIANCE (Jnr)									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.369	0.390	0.377	0.370	0.375	0.398	0.436	0.494	11.809
2	0.371	0.389	0.367	0.373	0.374	0.398	0.435	0.495	0.779
3	0.376	0.378	0.385	0.372	0.378	0.400	0.435	0.497	1.408
4	0.379	0.369	0.364	0.376	0.376	0.399	0.436	0.497	1.189
5	0.382	0.361	0.381	0.370	0.379	0.400	0.437	0.499	1.072
6	0.384	0.360	0.370	0.368	0.381	0.402	0.436	0.500	0.903
7	0.384	0.370	0.366	0.368	0.379	0.401	0.435	0.501	1.009
8	0.390	0.378	0.382	0.367	0.381	0.402	0.438	0.503	0.978
9	0.390	0.383	0.360	0.374	0.382	0.401	0.437	0.505	0.711
10	0.391	0.385	0.377	0.368	0.377	0.401	0.436	0.507	0.713
AVERAGE	**0.382**	**0.376**	**0.373**	**0.370**	**0.378**	**0.400**	**0.436**	**0.500**	**2.057**
Min.	**0.360**	**0.360**	**0.360**	**0.367**	**0.374**	**0.398**	**0.435**	**0.494**	**0.711**
Max.	**0.391**	**0.390**	**0.385**	**0.376**	**0.382**	**0.402**	**0.438**	**0.507**	**11.809**
Standard dev.	**0.008**	**0.011**	**0.009**	**0.003**	**0.003**	**0.001**	**0.001**	**0.004**	**3.433**
Differences between 0.1 kPa & 3.20 kPa		**6.4**							
Differences between 0.1 kPa & 6.40kPa		**15.9**							

Table D.21: Recovery of 5% PMB at temperature 60°C (Repeated test)

5% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	77.836	83.407	82.518	0	81.690	82.891	79.708	9.056	0
2	85.405	88.627	86.850	0	85.184	84.835	81.151	75.483	0
3	83.624	88.677	88.487	0	86.610	85.611	82.566	75.353	0
4	88.523	90.823	89.198	0	87.347	86.319	82.124	77.014	0
5	89.612	90.970	90.349	0	88.152	87.192	83.068	76.662	0
6	90.325	91.394	90.605	0	88.627	87.632	82.697	76.824	0
7	90.941	89.560	90.812	0	89.174	87.430	83.437	76.731	0
8	88.572	91.514	91.426	0	89.703	87.170	82.658	77.449	0
9	87.372	92.330	91.880	0	90.125	87.103	83.629	77.348	0
10	89.766	91.773	91.828	0	90.347	87.301	82.946	77.612	0
AVERAGE	**87.198**	**89.908**	**89.395**	**0**	**87.696**	**86.348**	**82.398**	**69.953**	**0**
Min.	**77.836**	**83.407**	**82.518**	**0**	**81.690**	**82.891**	**79.708**	**9.056**	**0**
Max.	**90.941**	**92.330**	**91.880**	**0**	**90.347**	**87.632**	**83.629**	**77.612**	**0**
Standard dev.	**3.993**	**2.617**	**2.891**	**0**	**2.665**	**1.508**	**1.174**	**21.411**	**0**
Differences between 0.1 kPa & 3.20 kPa	**4.0**								
Differences between 0.1 kPa & 6.40kPa	**8.4**								

Table D.22: Non-recoverable of 5% PMB at temperature 60°C (Repeated test)

5% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (Jnr)									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.032	0.024	0.026	0.000	0.028	0.026	0.033	1.279	804.297
2	0.021	0.016	0.019	0.000	0.023	0.023	0.030	0.043	987.109
3	0.023	0.016	0.017	0.000	0.020	0.022	0.028	0.043	989.844
4	0.016	0.013	0.016	0.000	0.019	0.021	0.029	0.040	1013.672
5	0.015	0.013	0.014	0.000	0.018	0.020	0.027	0.041	1043.750
6	0.014	0.012	0.014	0.000	0.017	0.019	0.028	0.040	1065.234
7	0.013	0.015	0.014	0.000	0.016	0.019	0.027	0.041	1089.063
8	0.016	0.012	0.013	0.000	0.015	0.020	0.028	0.039	1000.391
9	0.018	0.011	0.012	0.000	0.015	0.020	0.026	0.039	905.859
10	0.014	0.012	0.012	0.000	0.015	0.020	0.027	0.039	585.938
AVERAGE	**0.018**	**0.014**	**0.016**	**0.000**	**0.019**	**0.021**	**0.028**	**0.164**	**948.516**
Min.	**0.012**	**0.011**	**0.012**	**0.000**	**0.015**	**0.019**	**0.026**	**0.039**	**585.938**
Max.	**0.032**	**0.024**	**0.026**	**0.000**	**0.028**	**0.026**	**0.033**	**1.279**	**1089.063**
Standard dev.	**0.006**	**0.004**	**0.004**	**0.000**	**0.004**	**0.002**	**0.002**	**0.392**	**151.534**
Differences between 0.1 kPa & 3.20 kPa	**47.0**								
Differences between 0.1 kPa & 6.40kPa	**97.4**								

Table D.23: Recovery of 7% PMB at temperature 60°C (Repeated test)

7% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	64.893	81.233	85.487	0	87.073	88.897	87.433	86.103	0.270
2	68.585	82.971	88.964	0	89.666	91.026	89.229	87.349	48.609
3	73.540	84.411	89.936	0	90.873	91.737	90.365	88.658	32.532
4	72.148	82.767	91.316	0	91.419	92.325	91.199	88.519	32.789
5	72.854	85.801	91.433	0	91.955	92.499	91.342	88.506	19.542
6	74.086	86.231	91.703	0	92.380	92.681	91.357	89.412	39.979
7	76.896	85.585	91.654	0	92.595	92.702	91.349	89.184	59.810
8	79.746	89.144	92.816	0	92.882	92.708	91.255	89.317	52.771
9	74.586	86.392	93.031	0	92.901	92.797	91.323	89.983	41.123
10	73.216	87.912	92.918	0	93.343	92.794	91.635	89.588	35.494
AVERAGE	**73.055**	**85.245**	**90.926**	**0**	**91.509**	**92.017**	**90.649**	**88.662**	**36.292**
Min.	**64.893**	**81.233**	**85.487**	**0**	**87.073**	**88.897**	**87.433**	**86.103**	**0.270**
Max.	**79.746**	**89.144**	**93.031**	**0**	**93.343**	**92.797**	**91.635**	**89.983**	**59.810**
Standard dev.	**4.091**	**2.430**	**2.308**	**0**	**1.909**	**1.235**	**1.334**	**1.164**	**17.057**
Differences between 0.1 kPa & 3.20 kPa	**-7.9**								
Differences between 0.1 kPa & 6.40kPa	**-6.3**								

Table D.24: Non-recoverable of 7% PMB at temperature 60°C (Repeated test)

7% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.032	0.017	0.013	0.000	0.012	0.010	0.011	0.013	31.801
2	0.028	0.015	0.010	0.000	0.009	0.008	0.010	0.012	0.093
3	0.023	0.014	0.009	0.000	0.008	0.007	0.009	0.011	0.184
4	0.024	0.016	0.008	0.000	0.007	0.007	0.008	0.011	0.183
5	0.024	0.013	0.008	0.000	0.007	0.007	0.008	0.011	0.370
6	0.024	0.012	0.007	0.000	0.007	0.007	0.008	0.010	0.136
7	0.021	0.013	0.007	0.000	0.006	0.006	0.008	0.010	0.061
8	0.018	0.009	0.006	0.000	0.006	0.006	0.008	0.010	0.082
9	0.022	0.012	0.006	0.000	0.006	0.006	0.008	0.009	0.131
10	0.024	0.011	0.006	0.000	0.006	0.006	0.007	0.010	0.167
AVERAGE	**0.024**	**0.013**	**0.008**	**0.000**	**0.007**	**0.007**	**0.008**	**0.011**	**3.321**
Min.	**0.006**	**0.009**	**0.006**	**0.000**	**0.006**	**0.006**	**0.007**	**0.009**	**0.061**
Max.	**0.032**	**0.017**	**0.013**	**0.000**	**0.012**	**0.010**	**0.011**	**0.013**	**31.801**
Standard dev.	**0.004**	**0.002**	**0.002**	**0.000**	**0.002**	**0.001**	**0.001**	**0.001**	**10.007**
Differences between 0.1 kPa & 3.20 kPa	**-46.3**								
Differences between 0.1 kPa & 6.40kPa	**-36.1**								

Table D.25: Recovery of Pen binder at temperature 70°C

Pen 40/60									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	-2.500	-1.210	0.042	0.229	-0.062	-0.102	-0.317	-0.510	-0.772
2	-2.283	-1.114	0.000	0.271	-0.052	-0.153	-0.316	-0.555	-1.898
3	-2.293	-0.872	0.085	0.251	0.021	-0.152	-0.364	-0.487	-5.775
4	-2.468	-0.699	0.000	0.230	0.073	-0.152	-0.315	-0.505	-1485.227
5	-2.477	-0.850	0.084	0.272	0.000	-0.152	-0.362	-0.565	-637.040
6	-2.670	-0.946	0.084	0.272	0.010	-0.152	-0.339	-0.586	-609.375
7	-2.710	-1.032	0.084	0.273	0.052	-0.152	-0.289	-0.604	-641.996
8	-3.214	-1.088	0.042	0.209	0.042	-0.152	-0.313	-0.562	-608.607
9	-3.098	-1.158	0.169	0.210	-0.010	-0.157	-0.313	-0.564	0
10	-3.328	-1.228	0.210	0.105	0.010	-0.152	-0.362	-0.585	0
AVERAGE	**-2.704**	**-1.020**	**0.080**	**0.232**	**0.008**	**-0.148**	**-0.329**	**-0.552**	**0**
Min.	**-3.328**	**-1.228**	**0.000**	**0.105**	**-0.062**	**-0.157**	**-0.364**	**-0.604**	**0**
Max.	**-2.283**	**-0.699**	**0.210**	**0.273**	**0.073**	**-0.102**	**-0.289**	**-0.487**	**0**
Standard dev.	**0.380**	**0.174**	**0.067**	**0.052**	**0.043**	**0.016**	**0.026**	**0.039**	**0**
Differences between 0.1 kPa & 3.20 kPa	**85.5**								
Differences between 0.1 kPa & 6.40kPa	**67.7**								

Table D.26: Non-recoverable of Pen binder at temperature 70°C

Pen 40/60									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	0.05 kPa	0.1 kPa	0.40 kPa	0.80 kPa	1.60 kPa	3.2 kPa	6.4 kPa	12.8 kPa	25.6 kPa
1	6.068	5.940	5.885	5.983	6.047	6.109	6.438	6.928	17.344
2	6.004	5.991	5.930	5.970	6.056	6.153	6.441	7.077	14.887
3	5.978	5.898	5.910	5.958	6.055	6.172	6.464	7.091	24.539
4	5.978	5.903	5.920	5.968	6.026	6.191	6.461	7.159	1852.734
5	5.958	5.935	5.913	5.959	6.037	6.181	6.503	7.230	2143.750
6	6.076	5.867	5.923	5.953	6.024	6.184	6.483	7.370	2071.875
7	6.064	5.969	5.918	5.940	6.003	6.184	6.505	7.550	2154.688
8	6.102	5.945	5.923	5.955	5.980	6.194	6.503	7.549	2067.969
9	6.056	5.941	5.895	5.941	5.978	5.963	6.506	7.516	0.000
10	6.024	6.016	5.935	5.960	5.968	6.194	6.500	7.523	0.000
AVERAGE	**6.031**	**5.941**	**5.915**	**5.959**	**6.017**	**6.153**	**6.480**	**7.299**	**1034.779**
Min.	**5.885**	**5.867**	**5.885**	**5.940**	**5.968**	**5.963**	**6.438**	**6.928**	**0.000**
Max.	**6.102**	**6.016**	**5.935**	**5.983**	**6.056**	**6.194**	**6.506**	**7.550**	**2154.688**
Standard dev.	**0.049**	**0.044**	**0.015**	**0.013**	**0.033**	**0.072**	**0.027**	**0.232**	**1081.850**
Differences between 0.1 kPa & 3.20 kPa	**3.6**								
Differences between 0.1 kPa & 6.40kPa	**9.1**								

Table D.27: Recovery of 3% PMB at temperature 70°C

3% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	9.176	11.351	10.233	9.524	6.805	4.965	3.443	1.985	0.850
2	10.510	11.896	10.926	9.287	7.271	4.971	3.510	1.971	-2.267
3	10.646	12.797	11.764	9.921	7.170	5.044	3.438	1.890	-277.548
4	11.342	12.478	11.492	9.215	6.940	4.949	3.435	1.812	100.000
5	12.283	13.801	11.641	9.784	7.078	5.126	3.357	1.872	0
6	12.211	13.341	12.184	9.353	7.220	4.919	3.286	1.798	0
7	12.784	13.634	11.745	9.620	7.025	4.923	3.268	1.722	0
8	12.513	14.007	11.599	9.267	6.869	4.917	3.263	1.753	0
9	12.834	13.306	11.869	9.353	7.020	4.853	3.113	1.610	0
10	13.533	14.589	11.246	9.124	7.083	4.923	3.030	1.669	0
AVERAGE	**11.783**	**13.120**	**11.470**	**9.445**	**7.048**	**4.959**	**3.314**	**1.808**	**0**
Min.	**9.176**	**11.351**	**10.233**	**9.124**	**6.805**	**4.853**	**3.030**	**1.610**	**0**
Max.	**13.533**	**14.589**	**12.184**	**9.921**	**7.271**	**5.126**	**3.510**	**1.985**	**0**
Standard dev.	**1.335**	**0.994**	**0.553**	**0.260**	**0.149**	**0.076**	**0.154**	**0.124**	**0**
Differences between 0.1 kPa & 3.20 kPa	**62.2**								
Differences between 0.1 kPa & 6.40kPa	**74.7**								

Table D.28: Non-recoverable of 3% PMB at temperature 70°C

3% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	1.548	1.562	1.553	1.568	1.652	1.765	1.928	2.199	3.051
2	1.572	1.496	1.541	1.575	1.642	1.768	1.933	2.215	88.125
3	1.549	1.506	1.517	1.566	1.651	1.771	1.931	2.230	955.078
4	1.457	1.522	1.517	1.576	1.659	1.771	1.933	2.244	0.000
5	1.438	1.449	1.514	1.568	1.658	1.758	1.934	2.252	0.000
6	1.511	1.533	1.503	1.575	1.654	1.770	1.931	2.262	0.000
7	1.530	1.457	1.505	1.574	1.654	1.774	1.942	2.274	0.000
8	1.514	1.498	1.519	1.579	1.653	1.777	1.945	2.277	0.000
9	1.436	1.479	1.506	1.575	1.656	1.777	1.945	2.292	0.000
10	1.441	1.446	1.519	1.581	1.656	1.774	1.950	2.301	0.000
AVERAGE	**1.500**	**1.495**	**1.519**	**1.574**	**1.653**	**1.770**	**1.937**	**2.255**	**104.625**
Min.	**1.503**	**1.446**	**1.503**	**1.566**	**1.642**	**1.758**	**1.928**	**2.199**	**0.000**
Max.	**1.572**	**1.562**	**1.553**	**1.581**	**1.659**	**1.777**	**1.950**	**2.301**	**955.078**
Standard dev.	**0.052**	**0.038**	**0.016**	**0.005**	**0.005**	**0.006**	**0.008**	**0.033**	**300.090**
Differences between 0.1 kPa & 3.20 kPa	**18.4**								
Differences between 0.1 kPa & 6.40kPa	**29.6**								

Table D.29: Recovery of 5% PMB at temperature 70°C

5% SBS PMB									
% RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	67.775	67.775	68.113	64.053	57.978	50.043	39.996	4.138	0
2	73.972	73.972	69.804	66.313	58.911	50.893	40.881	15.458	0
3	75.627	75.627	71.589	66.378	59.224	50.673	40.650	19.739	0
4	78.482	78.482	73.478	67.024	59.320	50.565	40.428	30.466	0
5	78.420	78.420	73.975	66.807	59.698	50.539	40.513	30.369	0
6	78.116	78.116	73.420	66.432	59.817	50.308	40.499	29.189	0
7	79.110	79.110	72.694	66.673	59.417	49.898	40.389	28.297	0
8	81.589	81.589	72.111	66.622	59.433	49.899	40.425	28.175	0
9	82.444	82.444	73.220	66.971	59.617	49.478	39.910	27.844	0
10	79.302	79.302	74.411	66.156	59.647	49.182	39.330	26.920	0
AVERAGE	**77.484**	**77.484**	**72.282**	**66.343**	**59.306**	**50.148**	**40.302**	**24.060**	**0**
Min.	**67.775**	**67.775**	**68.113**	**64.053**	**57.978**	**49.182**	**39.330**	**4.138**	**0**
Max.	**82.444**	**82.444**	**74.411**	**67.024**	**59.817**	**50.893**	**40.881**	**30.466**	**0**
Standard dev.	**4.213**	**4.213**	**1.978**	**0.853**	**0.536**	**0.548**	**0.444**	**8.525**	**0**
Differences between 0.1 kPa & 3.20 kPa	**35.3**								
Differences between 0.1 kPa & 6.40kPa	**48.0**								

Table D.30: Non-recoverable of 5% PMB at temperature 70°C

5% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (J_{nr})									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.205	0.103	0.207	0.236	0.283	0.362	0.513	7.512	0.000
2	0.162	0.081	0.192	0.219	0.278	0.361	0.516	1.859	0.000
3	0.152	0.076	0.179	0.219	0.276	0.367	0.528	1.395	0.000
4	0.133	0.066	0.168	0.215	0.277	0.369	0.534	0.781	0.000
5	0.134	0.067	0.168	0.217	0.275	0.373	0.533	0.795	0.000
6	0.135	0.067	0.173	0.221	0.275	0.378	0.532	0.819	0.000
7	0.128	0.064	0.176	0.218	0.278	0.383	0.532	0.816	0.000
8	0.111	0.056	0.177	0.220	0.277	0.386	0.534	0.809	0.000
9	0.107	0.053	0.169	0.217	0.277	0.393	0.543	0.808	0.000
10	0.126	0.063	0.163	0.224	0.279	0.398	0.549	0.825	0.000
AVERAGE	**0.139**	**0.070**	**0.177**	**0.220**	**0.278**	**0.377**	**0.531**	**1.642**	**0.000**
Min.	**0.163**	**0.053**	**0.163**	**0.215**	**0.275**	**0.361**	**0.513**	**0.781**	**0.000**
Max.	**0.205**	**0.103**	**0.207**	**0.236**	**0.283**	**0.398**	**0.549**	**7.512**	**0.000**
Standard dev.	**0.029**	**0.014**	**0.013**	**0.006**	**0.002**	**0.013**	**0.011**	**2.093**	**0.000**
Differences between 0.1 kPa & 3.20 kPa	**441.6**								
Differences between 0.1 kPa & 6.40kPa	**663.2**								

Table D.31: Recovery of 7% PMB at temperature 70°C

7% SBS PMB									
RECOVERY									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	61.511	82.959	64.714	60.871	57.451	52.215	46.708	38.811	17.212
2	68.036	71.518	67.697	64.836	58.674	53.353	48.047	38.824	23.776
3	71.068	72.855	68.286	65.481	59.075	53.647	48.201	38.210	22.839
4	73.707	74.546	67.937	63.631	59.481	53.975	48.100	37.956	22.525
5	72.999	74.130	67.915	64.490	59.539	54.103	48.345	37.264	21.617
6	73.859	74.164	68.128	65.962	58.908	53.951	48.653	36.699	19.971
7	73.784	73.942	69.619	64.010	59.530	54.083	48.861	35.946	18.811
8	77.593	75.257	70.303	64.028	59.698	54.025	48.515	35.256	18.273
9	74.027	75.020	69.622	66.149	58.849	53.705	47.716	34.194	18.358
10	77.453	74.710	69.490	64.595	59.423	53.522	47.220	33.162	17.757
AVERAGE	**72.404**	**74.910**	**68.371**	**64.405**	**59.063**	**53.658**	**48.037**	**36.632**	**20.114**
Min.	**61.511**	**71.518**	**64.714**	**60.871**	**57.451**	**52.215**	**46.708**	**33.162**	**17.212**
Max.	**77.593**	**82.959**	**70.303**	**66.149**	**59.698**	**54.103**	**48.861**	**38.824**	**23.776**
Standard dev.	**4.722**	**3.035**	**1.578**	**1.500**	**0.664**	**0.567**	**0.662**	**1.959**	**2.382**
Differences between 0.1 kPa & 3.20 kPa	**28.4**								
Differences between 0.1 kPa & 6.40kPa	**35.9**								

Table D.32: Non-recoverable of 7% PMB at temperature 70°C

7% SBS PMB									
NON-RECOVERABLE CREEP COMPLIANCE (Jnr)									
Cycle	**0.05 kPa**	**0.1 kPa**	**0.40 kPa**	**0.80 kPa**	**1.60 kPa**	**3.2 kPa**	**6.4 kPa**	**12.8 kPa**	**25.6 kPa**
1	0.158	0.119	0.139	0.154	0.171	0.199	0.240	0.326	0.791
2	0.128	0.109	0.129	0.138	0.167	0.195	0.237	0.333	0.547
3	0.114	0.102	0.127	0.137	0.165	0.194	0.238	0.338	0.565
4	0.103	0.096	0.127	0.144	0.162	0.192	0.241	0.344	0.578
5	0.104	0.096	0.124	0.139	0.162	0.192	0.241	0.355	0.602
6	0.101	0.095	0.121	0.135	0.166	0.193	0.241	0.366	0.637
7	0.101	0.096	0.116	0.142	0.163	0.193	0.242	0.375	0.646
8	0.087	0.091	0.115	0.141	0.162	0.194	0.247	0.387	0.639
9	0.100	0.092	0.121	0.134	0.166	0.197	0.252	0.398	0.625
10	0.086	0.093	0.123	0.141	0.164	0.198	0.257	0.406	0.653
AVERAGE	**0.108**	**0.099**	**0.124**	**0.140**	**0.165**	**0.195**	**0.244**	**0.363**	**0.628**
Min.	**0.115**	**0.091**	**0.115**	**0.134**	**0.162**	**0.192**	**0.237**	**0.326**	**0.547**
Max.	**0.158**	**0.119**	**0.139**	**0.154**	**0.171**	**0.199**	**0.257**	**0.406**	**0.791**
Standard dev.	**0.021**	**0.009**	**0.007**	**0.006**	**0.003**	**0.002**	**0.006**	**0.028**	**0.068**
Differences between 0.1 kPa & 3.20 kPa	**96.9**								
Differences between 0.1 kPa & 6.40kPa	**146.3**								

D.2 Wheel Tracking Test (WTT)

Table D.33: A summary outcome of the WTT

Slab No.	Rut rate (mm/hr)	Rut depth (mm)	Average Rut depth (mm)	SBS percentage by mass
14-1172	0.62	1.84	**2.16**	**Conventional**
14-1173	0.86	2.5		
14-1174	0.56	2.14		
14-1175	0.16	1.85	**2.035**	**3 % SBS**
14-1176	0.82	2.22		
14-1177	0.35	1.14	**1.295**	**5 % SBS**
14-1178	0.18	1.45		
14-1179	0.22	1.29	**1.37**	**7 % SBS**
14-1180	0.46	1.45		

D.3 Indirect Tensile Stiffness Modulus Test (ITSMT)

Table D.34: A summary outcome of the ITSMT

Specimen No.	Stiffness modulus (MPa) 1st diameter	Stiffness modulus (MPa) 2nd diameter	Mean value (Mpa)	Average of each percentage	SBS percentage by mass (%)
14-1384	4177	4123	4150	**4,629**	**Conventional**
14-1385	5027	4907	4967		
14-1386	4400	4186	4293		
14-1387	4574	4309	4441.5		
14-1388	5494	5088	5291		
14-1390	8226	7258	7742	**6,505**	**3 % SBS**
14-1391	7188	7183	7185.5		
14-1392	6176	5904	6040		
14-1393	4992	5113	5052.5		
14-1394	9947	9582	9764.5	**9,005**	**5 % SBS**
14-1395	8963	8212	8587.5		
14-1396	9103	8856	8979.5		
14-1397	9001	8376	8688.5		
14-1398	9132	8328	8730	**9,401**	**7 % SBS**
14-1399	9842	10054	9948		
14-1400	9546	9598	9572		
14-1401	9438	9272	9355		

D.4 Repeated Load Axial Test (RLAT)

Table D.35: A summary outcome of the RLAT

Specimen No.	Percent strain at 100 pulses	Percent strain at 1000 pulses	Percent strain at 1400 pulses	Percent strain at 1800 pulses	Average stain per mixture (%)	SBS percentage by mass (%)
14-1384	1.3112	2.2836	2.4277	2.5287		
14-1385	0.8901	1.8322	1.9978	2.1056		
14-1386	0.5253	1.2308	1.3231	1.3887	**2.26826**	**Conventional**
14-1387	1.3356	2.1811	2.2912	2.3927		
14-1388	1.8367	2.7018	2.8427	2.9256		
14-1390	0.4972	0.841	0.906	0.9562		
14-1391	0.4373	1.0043	1.122	1.2054	**1.089975**	**3 % of SBS**
14-1392	0.4286	0.9392	1.0223	1.0791		
14-1393	0.5008	0.9628	1.0538	1.1192		
14-1394	0.2999	0.5205	0.5602	0.5847		
14-1395	0.6062	0.877	0.925	0.9625	**0.80755**	**5 % of SBS**
14-1396	0.4179	0.636	0.6806	0.7198		
14-1397	0.483	0.8366	0.9069	0.9632		
14-1398	0.3022	0.4874	0.5273	0.5529		
14-1399	0.3955	0.5837	0.6196	0.6408	**0.76**	**7 % of SBS**
14-1400	1.1787 R	1.4988 R	1.5564 R	1.599 R		
14-1401	0.7092	0.9977	1.0582	1.1012		

R: Represents unacceptable value due to instrumental errors in calibration

Appendix E: Test Risk Assessment Forms

E.1 Multiple Stress Creep Recovery Test (MSCRT)

Test Method Title	**Dynamic Shear Rheometer (DSR)**
Source (e.g. BS)	BSEN 14770:2005. IP 536-2005 IP PM CM/02. AASHTO T 315-05 Specification for Highways works clause 956: August 2008.
NTEC Ref (e.g. PT)	PT0024 & PT0124
Issue Number	06
Persons at Risk	Technical Staff, researchers, undergraduates.
General Hazards	Hot Bitumen, Ethylene Glycol, Compressed Air, use of hot cutting tools, Bunsen Burner, use of White spirit.
Substances Used (Refer to COSSH assessment for controls)	**Bitumen** **Ethylene Glycol** **White Spirit.** **Acetone**
Hazard Statement	**Bitumen,** Avoid inhalation of fumes **Ethylene Glycol,** Harmful if swallowed. **White Spirit,** May be fatal if swallowed and enters airways. Harmful if swallowed. Toxic to aquatic life with long lasting effects. Flammable liquid and vapour. **Acetone,** May cause drowsiness or dizziness. Causes serious eye irritation. Highly flammable liquid and vapour. Repeated exposure may cause skin dryness or cracking.
Appraisal	**Exposure**: Handling vessels containing hot bitumen. Pouring hot bitumen on to the DSR plates and then trimming the sample to size with warm tools. Working with cold baths up to −5°C. Cleaning the spindle and plates after testing with White Spirit-always remove from DSR before cleaning. (White Spirit should be put away after cleaning the spindle and plate). Making up a 20% solution of Ethylene Glycol and water as the cooling agent for the chillers. Make sure the Bunsen flame is switched off after trimming sample. **Controls**: Lab coat, safety glasses, safety shoes, heat resistant gloves. Nitrile disposable gloves.
Recommendations	Ensure spindle and base plate are cool before applying White Spirit or Acetone to minimise flashing.
Conclusion on Risk	**Normal Conditions-** LOW RISK of burns. In the event of a bitumen or oven burn run cold water over the burn and seek medical advice if required. **Emergency-** LOW RISK Risks are adequately controlled and no improvements are required

<table>
<tr><td colspan="2">Risk Assessment By</td><td>L Pont</td><td>Date</td><td>26/05/11</td><td>Signed</td><td></td></tr>
<tr><td colspan="7">REVIEW DETAILS (INCLUDES COSHH ASESSMENT)</td></tr>
<tr><td></td><td>Review Date</td><td>Signed</td><td colspan="4">Recommendations</td></tr>
</table>

E.2 Wheel Tracking Test (WTT)

Test Method Title	Determination of wheel tracking rate and depth				
Source (e.g. BS)	BS EN 12697-22:2003				
NTEC Ref (e.g. PT)	PT0028				
Issue Number	2				
Persons at Risk	Technical Staff, researchers, undergraduates.				
General Hazards	Warm Moulds containing Warm slabs Manual handling (less than 20kg)				
Substances Used (Refer to COSSH assessment for controls)	Talcum powder Asphaltic mixtures				
Hazard Statement	None listed				
Appraisal	**Exposure**: Handling of moulds up to 60°c Manual handling 20kg (maximum) **Controls**: : Lab coat, safety glasses, safety shoes, gloves,				
Recommendations	Manual handling course for lifting heavy items Trolley to carry slabs to and from balance Gloves for handling moulds above 45°C				
Conclusion on Risk	**Normal Conditions-** LOW RISK of manual handling injury **Emergency-** LOW RISK Risks are adequately controlled and no improvements are required.				
Risk Assessment By	M Winfield	**Date**	27/4/05	**Signed**	
Review Details					
	Review Date	**Signed**	**Recommendations**		

Test Method Title	Determination of wheel tracking rate and depth				
Source (e.g. BS)	BS598-110:1998				
NTEC Ref (e.g. PT)	PT0028				
Issue Number	3				
Persons at Risk	Technical Staff, researchers, undergraduates.				
General Hazards	Warm Moulds containing Warm slabs. Manual handling (less than 20kg).				
Substances Used (Refer to COSSH assessment for controls)	Talcum powder Asphaltic mixtures				
Hazard Statement	None listed.				
Appraisal	**Exposure**: Handling of moulds up to 60°c Manual handling 20kg (maximum) **Controls**: : Lab coat, safety glasses, safety shoes, gloves,				
Recommendations	Manual handling course for lifting heavy items Trolley to carry slabs to and from balance Gloves for handling moulds above 45°C				
Conclusion on Risk	**Normal Conditions-** LOW RISK of manual handling injury **Emergency-** LOW RISK Risks are adequately controlled and no improvements are required.				
Risk Assessment By	M Winfield	**Date**	27/4/05	**Signed**	
Review Details					
	Review Date	**Signed**	**Recommendations**		

E.3 Indirect Tensile Stiffness Modulus Test (ITSMT)

Test Method Title	**Indirect Stiffness Modulus of Bituminous Mixtures**
Source (e.g. BS)	DD213:1993 and BSEN12697-26:2004
NTEC Ref (e.g. PT)	PT0030
Issue Number	05
Persons at Risk	Technical Staff, researchers, undergraduates.
General Hazards	Compressed Air, Display Screen Equipment Use. Trapping fingers in test rigs.
Substances Used (Refer to COSSH assessment for controls)	Asphalt cores
Hazard Statement	None
Appraisal	**Exposure**: Handling 100mm and 150mm diameter bituminous cores tested at 20 ± 0.5°C **Controls**: Lab coat, safety glasses, safety shoes
Recommendations	**Keep fingers well away from the actuater during a test**
Conclusion on Risk	**Normal Conditions-** LOW RISK of trapped fingers in the testing apparatus, ensure fingers are well away from test jig once the test has started. Small risk from compressed air lines **Emergency-** LOW RISK Risks are adequately controlled and no improvements are required.

Risk Assessment By	M Winfield	**Date**	27/4/05	**Signed**	

Review Details			
	Review Date	**Signed**	**Recommendations**

E.4 Repeated Load Axial Test (RLAT)

Test Method Title	**Repeated Load Axial Test of Bituminous Mixtures Subject to Unconfined Dynamic Loading**				
Source (e.g. BS)	DD226:1996				
NTEC Ref (e.g. PT)	PT0031				
Issue Number	03				
Persons at Risk	Technical Staff, researchers, undergraduates.				
General Hazards	Compressed Air, Display Screen Equipment Use. Trapping fingers in test rigs. Use of a mixture of Silicone Grease and Graphite powder				
Substances Used (Refer to COSSH assessment for controls)	Bituminous cores, Graphite Powder Silicone Grease				
Hazard Statement	**Graphite powder:** Causes serious eye irritation. May cause respiratory irritation. **Silicone Grease:** None listed (wear gloves)				
Appraisal	**Exposure**: Handling 100mm and 150mm diameter bituminous cores tested at 30 ± 0.5°C and above **Controls**: Lab coat, safety glasses, safety shoes				
Recommendations	**Always wear rubber gloves and a dust mask when applying the silicone grease and graphite powder. Keep dust build up to a minimum, as graphite has an explosion hazard**				
Conclusion on Risk	**Normal Conditions-** LOW RISK of trapped fingers in the testing apparatus ensure fingers are well away from test jig once the test has started. Small risk from compressed air lines **Emergency-** LOW RISK Risks are adequately controlled and no improvements are required.				
Risk Assessment By	M Winfield	**Date**	27/4/05	**Signed**	
Review Details					
	Review Date	**Signed**	**Recommendations**		

Appendix F: Blending Process Form

NTEC TEST ORDER

Test Order Number: 12392

Job Number:	1540	**Date Of Order:**	13/06/2014
Notes:	3x 4kg sbs blends		

SampleNumber:	ProcedureNumber:	Completed:
14-1140	NTPTON030	
14-1140	PT0093	
14-1142	PT0093	
14-1144	PT0093	

Results Required:	27/06/2014	**Prepared By:**	lawrence
Retain Test Residue?	No	**Authorised By:**	lawrence
Report Due:		**Supervising Technician:**	lawrence
		Reported By:	

Keep 3kg for Mohammed Shosh

1 kg of each for sondis Taher

(MS)	(ST)
14-1140	14-1141
14-1142	14-1143
14-1144	14-1145

NOTTINGHAM TRANSPORTATION ENGINEERING CENTRE

BLENDING POLYMER MODIFIED BITUMENS

DIHP — WS/PT0093/ISSUE 2

Job Number	1540
Sample Number	**14-1142**
Test Order No.	12392
Date Result Required	27/06/2014
Residue to be retained (Y/N)	NO
Storage Location	Production

EQUIPMENT DETAILS			
	Equipment No.		Equipment No.
Oven	E 0607	Balance	E 0728

SAMPLE PREPARATION			
Sample obtained from	(Tin) / Binder Recovery / RTFOT / PAV / Other :		
Oven Temperature	180 °C	Heating period	150 mins

TEST PROCEDURE-BLENDING				
Clients Blend Reference (If applicable)				
Blending temperature range required by client	Minimum	190 °C	Maximum	170 °C
	BASE CONSTITUENT		POLYMER / FLUX/~~OTHER~~	
NTEC Sample Number	09-3073 (Bit)		07-2389 (SBS)	
Clients Reference (If applicable)				
Total Mass of Bitumen required by client	4000			
Percentage of each constituent required by client	95		5	
Mass Required	3800 g		200 g	
	SENIOR TECHNICIAN		CLIENT	
Blend CHECKED against clients requirements prior to blending	Date :		Date :	
	Signed :		Signed :	
Actual Mass (g)	3800		200	
Actual blending temperature	°C			
Polymer dispersion slide produced & checked (TICK)		Blend Time (mins)	100	

	Blended By	Checked By	Data Entry
Date	17/6/14	17/6/14	17/6/14
Signed	CP	CP	CP

NOTTINGHAM TRANSPORTATION ENGINEERING CENTRE

BLENDING POLYMER MODIFIED BITUMENS

DIHP — WS/PT0093/ISSUE 2

Job Number	1540
Sample Number	**14-1144**
Test Order No.	12392
Date Result Required	27/06/2014
Residue to be retained (Y/N)	NO
Storage Location	Production

EQUIPMENT DETAILS			
	Equipment No.		Equipment No.
Oven	E 0107	Balance	E 0724

SAMPLE PREPARATION			
Sample obtained from	(Tin) / Binder Recovery / RTFOT / PAV / Other :		
Oven Temperature	180 °C	Heating period	140 mins

TEST PROCEDURE-BLENDING				
Clients Blend Reference (If applicable)				
Blending temperature range required by client	Minimum	190 °C	Maximum	170 °C
	BASE CONSTITUENT		POLYMER / FLUX/OTHER	
NTEC Sample Number	09-3073 (BIT)		07-2389 (SBS)	
Clients Reference (If applicable)				
Total Mass of Bitumen required by client	4000			
Percentage of each constituent required by client	93		7	
Mass Required	3720 g		280 g	
	SENIOR TECHNICIAN		CLIENT	
Blend CHECKED against clients requirements prior to blending	Date :		Date :	
	Signed :		Signed :	
Actual Mass (g)	3720		280	
Actual blending temperature	°C			
Polymer dispersion slide produced & checked (TICK)		Blend Time (mins)	120	

	Blended By	Checked By	Data Entry
Date	17/6/14	17/6/14	17/6/14
Signed	[signature]	[signature]	[signature]

NOTTINGHAM TRANSPORTATION ENGINEERING CENTRE

BLENDING POLYMER MODIFIED BITUMENS

DIHP WS/PT0093/ISSUE 2

Job Number	1540
Sample Number	**14-1140**
Test Order No.	12392
Date Result Required	27/06/2014
Residue to be retained (Y/N)	NO
Storage Location	Production

EQUIPMENT DETAILS			
	Equipment No.		Equipment No.
Oven	E 0607	Balance	E 0728

SAMPLE PREPARATION			
Sample obtained from (Tin) / Binder Recovery / RTFOT / PAV / Other :			
Oven Temperature	180 °C	Heating period	150 mins

TEST PROCEDURE-BLENDING							
Clients Blend Reference (If applicable)							
Blending temperature range required by client	Minimum	190 °C		Maximum	170 °C		
	BASE CONSTITUENT			POLYMER / ~~FLUX/OTHER~~			
NTEC Sample Number	09-3073 (BIT)			07-2389 (SBS)			
Clients Reference (If applicable)							
Total Mass of Bitumen required by client	4000						
Percentage of each constituent required by client	97			3			
Mass Required	3880 g			120 g			
	SENIOR TECHNICIAN			CLIENT			
Blend CHECKED against clients requirements prior to blending	Date :			Date :			
	Signed :			Signed :			
Actual Mass (g)	3880			120			
Actual blending temperature	°C						
Polymer dispersion slide produced & checked (TICK)		Blend Time (mins)	90				

	Blended By	Checked By	Data Entry
Date	17-6-14	17-6-14	17/6/14
Signed	[signature]	[signature]	[signature]