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Performance Analysis of Thin Surface Course Systems used in England: a novel approach based on Viscous to Elastic Transition (VET) parameters

by

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ABSTRACT

This research explores, investigates and assesses the performance of Thin Surface Course Systems (TSCS) used on the Strategic Road Network (SRN) in England. Fretting is acknowledged to be the main defect for TSCS. The key factors causing fretting on TSCS include poor designs, poor adhesion between the binder and the aggregate, poor compaction, aggressive scuffing by the traffic, bitumen ageing and effect of climatic conditions/laying season. The research reviews design specifications, installation, maintenance and asset management strategies of TSCS in the United Kingdom, Europe, United States, New Zealand and South Africa. This was carried out to ascertain best practice for TSCS worldwide and proffer effective solutions to improve performance and durability for use on the SRN.

Findings from this research showed that most samples obtained from site had air void contents > 7%. Individual measurements of up to 19% were reported for some samples and the overall average air void content was 10.6%. The percentage of air void contents within the TSCS in England in comparison to other European countries is significantly higher. The study showed that the severity of fretting increases with high air void contents. High air void contents increase the permeability of the layer to air and water which makes the asphalt prone to stripping. This adversely impacts on the overall performance and durability of the TSCS.

The research showed that TSCS samples major fretting had lower stiffness values. Further to this, findings showed that most TSCS observed showed signs of fretting and/or other defects after around five years of being in service. This is interestingly in line with the warranty period required within Highways England specifications. However, this contradicts previous studies carried out in England where it was concluded that if a TSCS has performed well within the

first five years then it would continue to perform well for up to 10 years in service.

The study showed that samples with higher texture depth were found to have higher air void content. This is thought to be due to the loss of surface aggregates. Higher texture depths are attributed to higher levels of fretting for TSCS. The research provided evidence showing low binder penetration values could result in increased fretting of TSCS. The study showed that TSCS laid in the winter had an increased chance of fretting in comparison to TSCS laid outside of this season.

Based on the finding of this research study, it is therefore proposed to incorporate the following updates into Highways England (HE) design standard HD 30. This will help HE to understand the TSCS life expectancy performance within the network so that HE could move away from only 10-year cyclic TSCS replacement and develop a more intelligent Value Management approach based on the in-situ performance of TSCS rather than their age only.

- The assessment of binder rheology should be included as part of the scheme level survey to ascertain pavement conditions.
- Asphalt cores should be taken from locations representative of the site conditions.
- The recovered binder should subsequently be subjected to rheological testing to BS EN 14770 by applying the following test conditions:

    - The test frequencies should include 0.4 Hz and 1.59 Hz;
    - The test temperatures should cover the minimum range from 0ºC to 60ºC;
    - The temperature and complex modulus at which the phase angle value equals 45 degrees (T_{VET} and

G^*_{VET} respectively) when tested at a frequency of 0.4 Hz must be reported.

Plots of Viscous to Elastic Transition (VET) temperatures, T_{VET}, against their respective complex stiffness modulus, G^*_{VET}, provide a useful tool for establishing how changes in the properties of bituminous materials may be associated with different levels of age hardening and/or distress levels (cracked or uncracked sites).

The VET analysis developed in this study focuses on paving grade bitumen. Further studies and research focused on developing the VET analysis for polymer modified binders is recommended for future work. This is an important aspect in developing a comprehensive maintenance strategy for TSCS on the SRN.

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Finally, I would like to thank my wife who has always provided me with a lot of encouragement and support.

DECLARATION

The work and research presented and described in this PhD thesis was conducted at the University of Nottingham, Department of Civil Engineering, Nottingham Transportation Engineering Centre (NTEC) between January 2012 and July 2019.

I declare that the work is my own and has not been submitted for a degree of another university.

Arash Khojinian
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1. INTRODUCTION

1.1 Project Overview

Thin Surface Course Systems (TSCS) as detailed in Highways England (HE) advice note IAN 157/11 (2011) are “hot bituminous bound mixtures, machine-laid with a controlled screed paver onto a bond or tack coat. TSCS consist of aggregate, filler and a bituminous binder which may be modified by the addition of polymers, rubber, resins, fibres or fillers such as hydrated lime or cement” (IAN 157/11, 2011). On HE sites, TSCS are to be provided and installed in accordance with the Manual of Contract Documents for Highway Works (MCHW) Volume 1 Specification for Highway Works (SHW) Clause 942 (Highways England, 2018a). TSCS are typically laid at a thickness less than 50 mm.

TSCS have been used on the Strategic Road Network (SRN) in England since 1995 (IAN 157/11, 2011). TSCS have generally performed very well enabling Highways England (HE) to maintain their network using a material with reduced noise and installed with minimal disruptions to road users (Highways England, 2017). Significant experience and knowledge in the use of TSCS have been gained. However, it must be noted that there are apparent shortcomings with the use of TSCS (IAN 157/11, 2011). Firstly, recent experience shows that most TSCS have had premature failures limiting the serviceable life of the asphalt to 7-10 years as opposed to an average of 17 years based on experience in Europe (IAN 157/11, 2011). Surface disintegration (fretting) is acknowledged to be one of the central defects for TSCS (Sandberg et al., 2011; Khojinian, Parry and Thom, 2016).

Fretting is the progressive disintegration of TSCS due to the loss and dislodgement of aggregate particles from the asphalt matrix (Alabaster et al., 2015). It occurs when individual aggregate particles are lost under the action of traffic and environmental factors (Alabaster et al., 2015).
Fretting is defined as chemical and physical changes in the asphalt surfacing which can be caused by a combination of poor construction quality, environmental effects, and trafficking (Francken, 1998).

The premature failures of TSCS have been attributed to the poor condition of pavement substrates, severe winter conditions, increasing traffic loadings and poor construction techniques. These premature failures have often developed in a rapid manner (Khojinian, Parry and Thom, 2016). Premature failure of TSCS will result in early intervention at high costs (Khojinian, Parry and Thom, 2016).

HE manages annual vehicle-based traffic speed surveys for road condition measurements. This includes a basic measure of road surface condition (DFT, 2018). HE pavement management and investigation procedures are clearly defined and form part of the Value Management (VM) process (Atkins, 2013). HE VM provides a technical review of proposed treatment options and generates a VM score for the preferred improvement opportunity or renewal project (DFT, 2018). This VM score provides a measure used to prioritise projects and develop funded programs for road maintenance (DFT, 2018). This measure is not sufficiently developed to enable the failure of the surfacing to be predicted.

Robust evidence is required to demonstrate that HE is maximising the return on investment on the SRN (ORR, 2018). It is important for HE that road surfaces are durable and performing adequately in a manner that makes the SRN safer, improves customer satisfaction and supports the smooth flow of traffic (Highways England, 2018a). HE value management strategy provides the basis for the identification and prioritisation of assets for maintenance (KPMG, 2017). The failure to identify and investigate issues and defects on roads could result in further deterioration (DFT, 2018).

1.2 Problem Statement

Premature failures limit the serviceable life of TSCS to an average of 7 to 10 years. Surface disintegration (fretting) due to loss of bond between aggregate particles and the binder is acknowledged to be the main type of defect for TSCS. The factors that influence fretting are summarised in Table 1.

Table 1: Factors that Influence Fretting of TSCS

Internal

- Mix Design
- Binder Properties
- Installation
- Aggregate Size
- Aggregate/Binder Affinity

Traffic

- Lateral Stresses
- Fatigue Stresses

Environmental

- Ingress of Moisture
- Oxidisation

Substrate

- Substrate instability causing strains

Interface

- Mostly relevant where aggregate size is large relative to layer thickness

The potential factors causing/accelerating fretting include inappropriate aggregate grading, poor adhesion between the binder and the aggregate, poor compaction, aggressive scuffing by the traffic, bitumen ageing and effect of climatic conditions/laying season. These factors are often interdependent making it difficult to assess the theoretical potential to ravel of asphalt mixtures.

1.3 Research Objectives

In the context described in the above sections, the scope of this thesis is to increase the understanding of TSCS performance used in the UK network, in order to improve the management of maintenance strategies for the HE SRN. For this purpose, the overall aim is to provide an extensive and comprehensive literature review on the use of TSCS and develop and propose novel approaches and analyses to assess and predict TSCS performance in the UK network.

To achieve this, the key objectives of this thesis are:

- To carry out a comprehensive literature review of TSCS, from a global perspective, investigating my distresses of TSCS and factors affecting its performance and durability

- To review key empirical and fundamental mechanical tests assessing properties and performance of asphalt and bitumen.

- To review different approaches on the analysis of binder rheological properties as a proxy of material condition and performance, such as the Viscous to Elastic Transition (VET) analysis.

- To present and analyse key findings following a site visit to Germany to investigate, evaluate and assess the design and use of typical Stone Mastic Asphalt (SMA) TSCS in Germany, as opposed to UK TSCS.

- To conduct a comprehensive review and analysis of historical HE network TSCS condition data using Highways Agency Pavement Management System (HAPMS) database.

- To identify and select key sites on the SRN in order to undertaken further testing on cores and extracted bitumen.
- To analyse relationships between key factors affecting TSCS performance and durability, establishing possible correlations between TSCS safety and rideability condition measured on site and material empirical and fundamental properties.

- To develop and propose a novel method based on VET analysis, to evaluate performance of TSCS, as opposed to on-site measured conditions. This innovative approach would help identifying and predicting surface deterioration, enabling better understanding of TSCS durability.

- To provide guidelines and recommendations that improve the management and maintenance strategy for TSCS within HE SRN.

1.4 Thesis Outline

The present thesis describes the reviews and analyses carried out to increase the understanding of UK TSCS and propose a novel approach to assess its performance. To this end, the thesis is six chapters, as summarises in the following sections.

1.4.1 Chapter 1: Introduction

This chapter presents an introduction and overview of the study. The problem statement, the aims and objectives of the research are detailed in this chapter. This chapter presents the scope of works and chapter outline for the study.

1.4.2 Chapter 2: Literature Review of Thin Surface Course Systems

This chapter presents a detailed literature review introducing the concepts of Thin Surface Course Systems (TSCS), the durability of TSCS, current practices of using TSCS in the UK, Europe, The United States of America (USA), South Africa and New Zealand. The study presents the European design approaches and standards. The literature review provides conclusions and recommendations for using TSCS based on global experiences.

1.4.3 Chapter 3: Literature Review of Viscous to Elastic Transition (VET) Temperatures

This chapter provides discussions on the use of Viscous to Elastic Transition (VET) temperature analysis as a method for evaluating TSCS performance. Findings and concepts on the use of VET analysis are presented, considering experiences in France, the United Kingdom and the United States.

The major aim of this chapter is to identify the key factors of VET analysis for potential implementation as an analytical tool in scheme and network level surveys.

1.4.4 Chapter 4: Review and Analysis of German Stone Mastic Asphalt

This chapter provides a review of the mix design, material properties, surface characteristics and construction techniques used in Germany. This study presents key findings following a site visit to Germany to investigate, evaluate and assess the design and use of Stone Mastic Asphalts (SMA).

1.4.5 Chapter 5: Review and Analysis of Highways England Network Condition Data for Thin Surface Course Systems

This chapter aims to carry out a detailed review, investigation and analysis of HE network condition data for TSCS. The chapter makes use of information from Highways Agency Pavement Management System (HAPMS) to provide an overview of the current state of the SRN.

1.4.6 Chapter 6: Discussion, Conclusions and Recommendations

The chapter summarises the key discussion points following findings from Chapters 1 to 5. This chapter proffers options and solutions for updates to HE Design Manual for Roads and Bridges (DMRB). Key options include the need for introducing new assessment methods that can be used to evaluate the performance of TSCS. The chapter outline is summarised and presented in Figure 1.

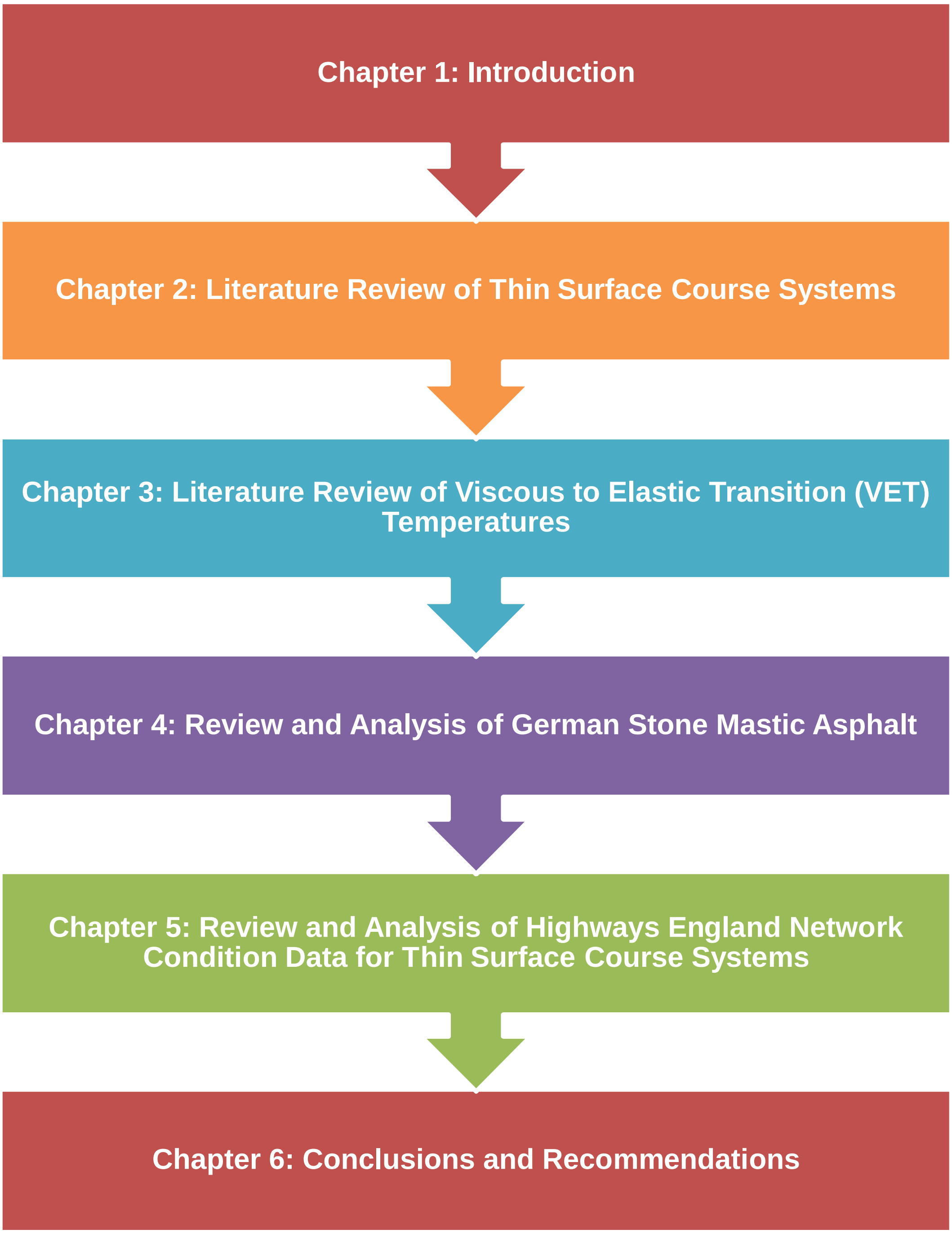

Figure 1: Thesis Outline

2. METHODOLOGY

This research aims to increase the understanding of TSCS performance used in the UK network, and improve the management of maintenance strategies for the HE SRN. To this end, specific research objectives are set, as described in Section 1.3.

In order to achieve the declared objectives, the overarching methodology that will be followed throughout the study is summarised below.

As an initial and essential task, a comprehensive literature review will be carried out. This will include studied features of Thin Surface Course Systems (TSCS) and relevant subjects through studying research and current research or research programs in order to form the required base knowledge and reveal the existing research gaps in the subject to emphasise the need for conducting the current research.

The fundamental questions to be answered are related to TSCS: life expectancy, mode of failures, and main factors affecting them. Thus, this review will include the identificationof TSCS defects and factors affecting its performance and durability as well as key empirical and fundamental mechanical tests assessing properties and performance of asphalt and bitumen.

The review of main tests will help identify traditional and innovative approaches to assess material condition and performance, such as the Viscous to Elastic Transition (VET) analysis.

The following step will be toconduct a comprehensive review and analysis of historical HE network TSCS condition data using Highways Agency Pavement Management System (HAPMS) database. This will help identify a number of suitable TSCS sites, some that have performed well, some where there is evidence of fretting or surface disintegration earlier than their intended serviceable life and others that appear to have reached the end of their serviceable life. Core samples will be extracted from the selected sites to enable further testing and investigation on asphalt and bitumen. 30 sites will be selected from the north east, east/southeast and south west of England.

The next step will be to devise and perform a comprehensive matrix of laboratory tests for determining the physical and mechanical properties of materials as well as the rheological behaviour characteristics of the binders. The main data gathered from the core samples will include the type of thin surfacing system if available, the aggregate size, binder content, binder type, percentage of air void, surfacing depth, road type, texture depth and visual condition.

Testing will include: Penetration grade and Softening Point determination; Dynamic Mechanical Analysis (DMA)/Frequency-Temperature Sweep test using a Dynamic Shear Rheometer over a range of different temperatures (5°C to 80°C) and frequencies (0.1Hz to 10Hz); evaluating the mechanical performance characteristics of the core TSCS mixtures to fully investigate the effect of lower mixing and compaction temperatures on the mechanical performance of the resulting mixtures; measuring the volumetric properties and compaction rate (to evaluate the compactability); performing the Indirect Tensile Stiffness Modulus (ITCY) test; and Complex Stiffness Modulus test under cyclic sinusoidal load measurement.

The investigation and interpretation of the test results, in relation to key factors and parameters retrieved from HAPMS database will enable further analysis and exploration of any possible correlation between the surface disintegration (visual conditions) and binder/mixture empirical and fundamental properties of TSCS.

As an additional innovative element, this thesis will explore the possibility of using VET analysis to evaluate performance of TSCS, as a proxy of on-site measured conditions. Exploring possible correlations with asphalt and binder properties as well as surface distresses would enable setting condition categories and thresholds to be used as an additional investigation tool.

The review undertaken, data analyses and novel approach proposed would increase the understanding of performance and durability of TSCS in the UK network and help provideguidelines and recommendations that improve the management and maintenance strategy within HE SRN.

3. LITERATURE REVIEW OF THIN SURFACE COURSE SYSTEMS

3.1 Introduction to Thin Surface Course Systems

Thin Surface Course Systems (TSCS) were originally designed in 1991 in France and Germany (Nicholls et al., 2002; IAN 157/11, 2011). The first thin surface course system was categorised as a Paver-Laid Surface Dressing (PLSD) (Nicholls et al., 2002). This material was slightly modified from the French design to achieve the required texture depth for a high-speed trunk road (Nicholls et al., 2002).

Nicholls et al., (2002) stated that traditional asphalt surface course layers for major roads were typically laid at a thickness of 40 mm. In 1990, asphalt surface course layers with thinner thicknesses were introduced and used on roads with reduced traffic such as county road networks (Nicholls et al., 2002). Findings showed that these roads were technically inferior with reduced mechanical and performance properties (Nicholls et al., 2002). In the 1990s, various versions of TSCS were used in the United Kingdom with increasing popularity and uptake due to properties that include reduced noise (Nicholls, 2002). In 1994, Stone Mastic Asphalt (SMA) was introduced from Germany and trialled in the United Kingdom (Nunn, 1994). Taking these factors into consideration, Nicholls et al., (2002) classified TSCS into the following categories:

- Paver-Laid Surface Dressing (PLSD): These are ultra-thin asphalt surfacing materials developed in France.
- Thin Asphalt Concrete (TAC): These are generally produced using polymer-modified binders.
- Thin Stone Mastic Asphalt (TSMA): These are generally produced using paving grade bitumen incorporating fibres.

- Multiple Surface Dressing (MSD): Binder and aggregate materials applied separately.
- Micro-Surfacing (MS): These are thick slurry surfacing materials produced generally with a modified binder.

Research findings show that the most common defects for TSCS are a loss of aggregate particles and cracking (Francken, 1998; Alabaster et al., 2015). The visual condition of TSCS can be classified by using a seven-point scale that comprises Excellent, Good, Moderate, Acceptable, Suspect, Poor and Bad.

Figure 2 provides a broad depiction of the various classifications and defects of typical TSCS. Fretting is shown in Figure 2 (d). These findings are following studies from over 137 sites and recordings of approximately 1000 visual condition surveys and observations (Nicholls et al., 2009).

(a) “Moderate” Condition

(b) “Acceptable” Condition

(c) “Suspect” Condition

(d) “Poor” Condition

Figure 2: Classification of the Visual Condition of Thin Surface Course Systems

Estimated serviceable lives for the TSCS identified above are detailed in Table 2.

Table 2: Estimated Serviceable Lives for Thin Surface Course Systems (Nicholls et al., 2009)

TSCS	Nominal Aggregate Size (mm)	No. of Sites	No. of Observations	Combined Estimate for Serviceable Lives (Years)
PLSD	14	9	32	13
	10	7	33	9.5
	6	1	6	6
TAC	14	32	82	>12
	10	33	134	>16
	6	8	34	>10
TSMA	14	49	197	>14
	10	9	30	>14
MSD	14	6	28	9
MS	6	4	22	8.5

***Extrapolated values**

3.2 Binder Characteristics Analysis

Nicholls et al., (2009) provided analysis on the influence of binder rheology on the performance of TSCS. It was expected that the type of thin surfacing system and the age of the surfacing would both influence the penetration and softening point of the binder recovered from thin surfacing systems. Results of the findings are detailed in Table 3, and Figure 3 to Figure 5.

Table 3: Average Measures for Recovered Binder Properties and Visual Conditions

Age	Visual Condition	Penetration	Softening Point
0	6.13	74.75	50.13
1	7.00	20.00	70.00
2	5.79	41.00	64.09
3	5.50	33.50	63.08
4	5.38	36.00	64.95
5	4.83	34.33	61.53
6	5.56	25.00	63.39
7	4.35	25.35	64.04
8	4.69	26.69	62.18
9	4.46	25.42	63.80
10	4.78	19.44	65.82
11	4.63	22.33	64.72
12	4.10	23.10	66.30
13	4.17	22.22	65.53
14	3.50	21.69	66.46
15	3.75	34.00	58.80

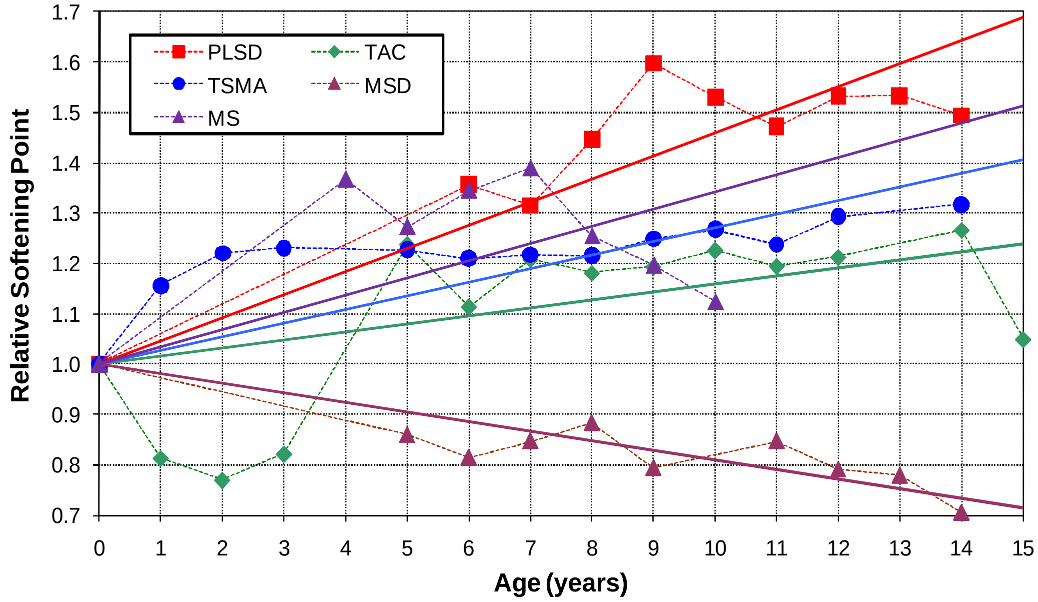

Figure 3: Change in Mean Recovered Softening Point Relative to Initial Value with Time (Nicholls et al., 2009)

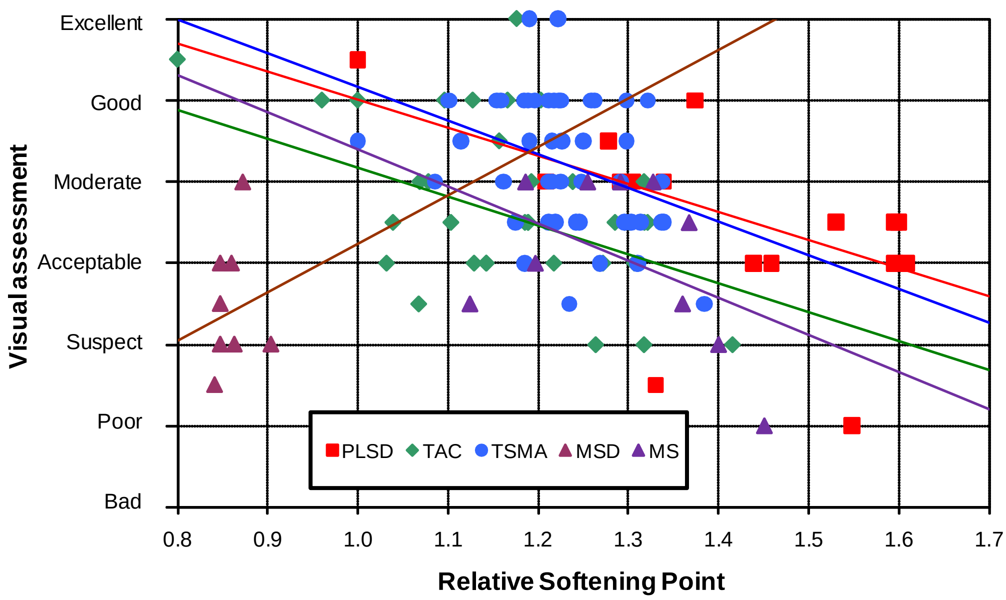

Figure 4: Mean Recovered Softening Point Relative to Visual Condition (Nicholls et al., 2009)

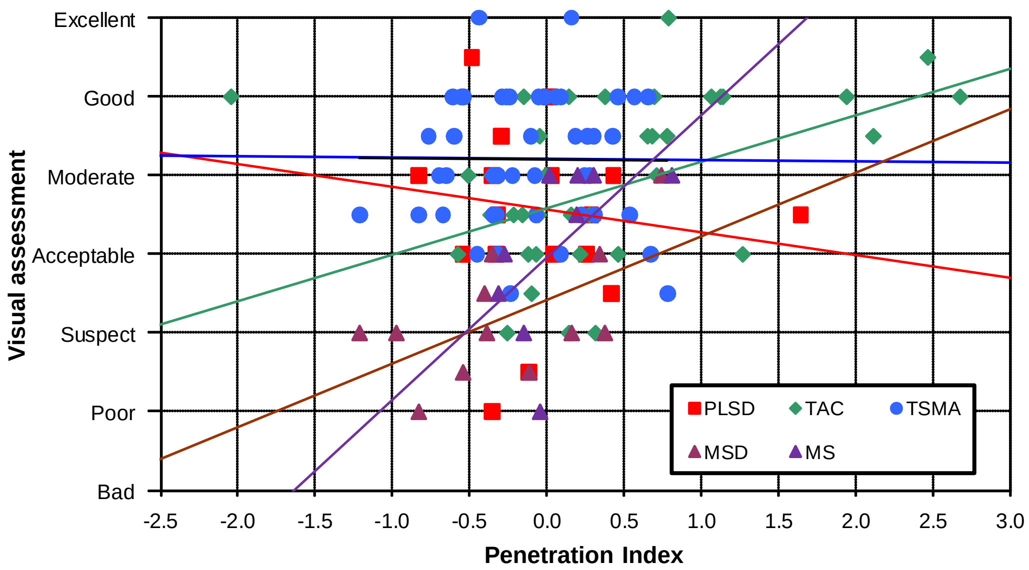

Figure 5: Penetration Index against Visual Condition (Nicholls et al., 2009)

The analysis by Nicholls et al., (2009) showed no clear relationship for either:

- The change of binder properties with time; or
- The visual condition of the surfacing with binder properties

3.3 Current Deterioration Models for Thin Surface Course Systems

TSCS are proprietary materials (IAN 157/11, 2011). They derive key mechanical properties from the contiguous coarse aggregate skeleton provided by their gradations and high coarse aggregate content (Nunn, 1994; Nunn 2004). Studies have shown that the typical form of distress in TSCS is fretting (Sandberg et al., 2011; Khojinian, Parry and Thom, 2016).

Atkins (2015) summarised key factors that initiate and propagate fretting in TSCS. Fretting tends to initiate from discontinuities, areas of damage or points of weakness in the asphalt mat such as joints, roundabouts, tight bends and steep gradients. Cracks, areas of poor compaction, areas with ironwork, traffic loops and the area where road markings have been removed using a high-pressure water jet could initiate fretting. Freeze-thaw cycles due to fluctuating weather conditions can increase fretting in TSCS (DFT, 2006; ADEPT, 2015).

In addition to fretting, cracking and delamination of the substrates are additional primary modes of distress and failure in TSCS (DFT, 2006; Nicholls et al., 2009; ADEPT, 2015). The long term mechanical and performance properties of TSCS are strongly dependent on the condition of the underlying pavement (DFT, 2006; Capita Symonds, 2007; Nicholls et al., 2009; Highways England, 2011; ADEPT, 2015).

Deterioration progresses quickly once these failures start. It is important for TSCS to be installed on a sound substrate. Further to this, asset management capable of detecting early signs of distress and a maintenance regime to reduce deterioration before widespread failure develops is important (Nicholls et al., 2009; ADEPT, 2015). Critical analyses and discussions focused on durability factors, design and materials approach used are presented in the sections below.

3.4 Durability Factors

This section of the report provides discussions on the major factors that influence the in-service performance of TSCS. The main factors are summarised under four categories as detailed below:

- Site Characteristics and Requirements.
- Mixture Properties.
- Best Practice and Guidance for Installation of TSCS.
- Maintenance Practices.

This information is summarised and presented as detailed in Table 4 to Table 7.

Table 4: Site Characteristics and Requirements (Atkins, 2015)

Factors	
Substrate Condition	A sound substrate is essential for achieving good mechanical and performance properties for TSCS. This has a direct influence on improving the service life of the TSCS (DFT, 2006; Nicholls et al., 2009; ADEPT, 2015).
Site Investigation and Preparation	It is important to engage and consult with all relevant stakeholders (specifier, designer and installer) involved in the project. This is most important in the site investigation and preparatory stages of the project to ascertain site conditions to inform the selection of an appropriate treatment solution for the project (DFT, 2006; Capita Symonds, 2007; Nicholls et al., 2009; ADEPT, 2015; Highways England, 2018a).
Site Conditions	The condition of the site has an influence on the choice of appropriate treatment options and the long term mechanical and performance properties of the installed material. Key factors to consider are detailed below: • Road Geometry – High-stress locations (roundabouts, approaches to junctions, tight bends and steep gradients) require specific design considerations ADEPT, 2014; Highways England, 2011; Highways England, 2018). • Traffic level/speed requires specific design considerations with respect to the Polished Stone Value (PSV) (Highways England, 2018a). • Drainage – Retention of water within the material and/or on the surface can lead to

	premature deterioration (Nicholls et al., 2013; ADEPT, 2015). • Climatic Conditions – Freeze-thaw cycles due to cyclic weather conditions can increase fretting in TSCS (DFT, 2006; ADEPT, 2015). • Existing pavement construction and nature of any existing defects/distress (ADEPT, 2015; Highways England, 2011).
Treatment Specification	It is essential that an accurate, detailed and comprehensive specification is provided to address the requirements and solution identified for each site (DFT, 2006; Capita Symonds, 2007; Nicholls et al., 2009; ADEPT, 2015).

Table 5: Mixture Properties (Atkins, 2015)

Factors	
Aggregate Properties	Aggregate properties play a major role in the durability of TSCS (Nicholls et al., 2009; ADEPT, 2015). TSCS are shown to be more durable in high-stress locations when smaller aggregate sizes are used (Highways England, 2011; Highways England, 2018a). The requirements for surface macrotexture of TSCS have been relaxed to facilitate the use of lower upper aggregate size materials (ADEPT, 2015; Highways England, 2011; Highways England, 2018a).
Binder Content	Binder content influences the performance and durability of TSCS (Nicholls et al., 2009). Recent specification developments have sought to avoid the use of low binder content materials (Transport Scotland, 2010; Highways England, 2018a).
Binder Properties	The rheological properties of binder play a major role in the performance of produced asphalt (Francken, 1998). The use of polymer modification and additives can be used to enhance the performance of asphalts (Francken, 1998).
Void Content	Compaction plays a major role in the performance of asphalts (Nicholls et al., 2008). The design and control of asphalt mixtures to ensure appropriate levels of air void content are achieved is important for long term performance (Transport Scotland, 2015; McHale, Carswell and Roe, 2011; Highways England, 2018a).
Bond Coat	The use of bond coat is an integral part of the TSCS system which has an important role in both promoting adhesion to the substrate and mitigating water penetration to the underlying pavement structure (DFT, 2006; ADEPT, 2015).

Table 6: Best Practice for Installation of Thin Surface Course Systems (Atkins, 2015)

Factors	
Compaction	Compaction plays a major role in the performance of asphalts (Nicholls et al., 2008). Poor compaction results in high air void contents. This has been linked to observed premature deterioration in TSCS (Nicholls et al., 2008). To achieve effective compaction, the material must be at adequate temperature during the compaction operation (Nicholls et al., 2008). The cooling of hot asphalt layers is affected by ambient temperature, wind speed, layer thickness, the presence of water or ice on the substrate, delays/interruptions to paving operations. It has been recommended that TSCS should be planned for the period April to October inclusive when conditions are most likely to be favourable (Highways England, 2011).
Layer Thickness	The layer thickness should be properly designed for considering the geometry of the road, aggregate size and compaction (Highways England, 2011).
Joints	Joints are frequently the point of initiation of distress in TSCS (DFT, 2006; Nicholls et al., 2009; ADEPT, 2015). Planning of works is required to minimise the number and location of joints during the execution of the works (DFT, 2006; Nicholls et al., 2009; ADEPT, 2015).
Substrate Preparation	To promote adhesion of the TSCS to the substrate, careful attention must be paid to the cleanliness, dryness and temperature of the substrate. Bond coat to the substrates is important (DFT, 2006; Nicholls et al., 2009; ADEPT, 2015). If required, necessary repairs to the substrate should be carried out in advance of paving the TSCS (ADEPT, 2014).
Optimum	Weather conditions at the time of laying have a major

Conditions	influence on long-term durability (ADEPT, 2015).

Table 7: Maintenance Practices (Atkins, 2015)

Factors	
Inspection Regime	It is important to develop an inspection regime capable of identifying early signs of distress to facilitate a planned approach.
Maintenance Regime	It is important to develop an asset management and maintenance regime for TSCS
Damage	Care should be taken to avoid damage through routine operations, such as cutting for detector loops or removal of markings using pressurised water systems that can provide an initiation point for deterioration (Nicholls et al., 2008; Highways England, 2011).
Works Records	Records of construction and maintenance are of value in determining maintenance treatment options and in supporting warranty claims in case of material failure (Nicholls et al., 2008).

3.5 Design Life

There is a perception in some sections of the UK pavement industry that modern thin surface courses do not offer a durable long-term solution (Atkins, 2015).

A summary of documented United Kingdom (UK) information focused on the expected service life of TSCS is presented in Table 8.

Table 8: Service Life of TSCS in the UK

Source	Reference	Service Life of TSCS in the UK
HD 37/99 "Bituminous Surfacing Materials and Techniques"	HD 37/99	7-15 years. Dependent on thickness, void content, traffic and underlying pavement condition. 15 years achievable for thicker TSCS. Expectation reduced from Continental experience due mainly to UK safety (texture) requirements.
IAN 157/11 "TSCS – Installation and Maintenance"	IAN 157/11	7-15 years (as HD37/99)
"Selection of Surfacing for Highway Pavements. Guidance for Local Authority Engineers"	ADEPT, 2015	Target 15 years. Absolute minimum 5 years. Typical minimum 10 years. Typical maximum 20 years.
"Identifying the Intervention Point for Preventative Maintenance of TSCS with Surface Dressing in Lincolnshire"	Neal, 2015	Minimum 5 years. Maximum 12/13 years. Typical 8 years.
"New Surface Course Specification for Scotland"	McHale, Carswell & Roe, 2011	Up to 10 years. However, identified two clusters of early failures: < 2 years and 4 to 5 years.
"Service life of asphalt	ADEPT and	15 years for 'designed' roads.

for asset management."	MPA, 2015	10 years for 'evolved' roads.
"Durability of TSCS: Part 1 Initial findings."	Nicholls et al., 2002	15 years for TSCS and Thin Asphalt Concrete (TAC).
"Durability of TSCS: Part 2 findings after 3 years."	Nicholls et al., 2004	> 15 years for TAC. >> 11.5 years for TSMA.
"Durability of TSCS: Part 3 findings after 6 years."	Nicholls et al., 2007	12-13 years for 10 or 14mm TAC. 15 years for 14 mm TSMA. > 15 years for 10 mm TSMA.
"Durability of TSCS: Part 4 Final report after nine years' monitoring."	Nicholls et al., 2009	10 mm TAC > 16 years. 14 mm TAC > 12 years. 14 and 10 mm TSMA > 14 years.
"Optimum Interventions for Thin Surfacing Maintenance"	Atkins, 2013	Average age at replacement 8.5 years. Range 2 years to 13 years.

3.6 United Kingdom Design Approach

TSCS are currently the only permitted option for a surface course on the SRN in England without specific departure approval from HE. TSCS are specified under Clause 942 of the Specification for Highway Works (Highways England, 2018a) and detailed in (Highways England, 2018a). In addition to this, TSCS must comply with the general requirements for bituminous materials presented in Clauses 901 to 903 of (Highways England, 2018a). Advice on the application and implementation of the specification is given in the accompanying Notes for Guidance (Highways England, 2018a).

TSCS for use on the SRN must demonstrate acceptable in-service performance. This is achieved using an accredited third-party product acceptance and accreditation schemes. This must also include a System Installation Performance Trial (SIPT).
TSCS are also subject to performance guarantees of two years for both surface texture and visual condition, and five years for surface integrity (Highways England, 2018a).

Continued monitoring, research and development of TSCS have resulted in a series of amendments to Clause 942 (Highways England, 2018a). These amendments include a requirement for minimum binder content dependent on aggregate size and material type. Further to this, there are requirements for minimum and maximum air voids for both SIPT (2% to 6%) and design voids when specified in contract specific appendix 7/1 (1% to 5%) (Highways England, 2018a). The current update includes a requirement for moisture susceptibility. Currently, this is specified as ≥ ITSR 70% in accordance with BS EN 12697-12.

3.6.1 Governing Standard BS EN 13108

BS EN 13108 ‘Bituminous Mixtures – Material Specifications’ is the British Standard (BS) issue of the Harmonised European Product Standard for Bituminous Mixtures. It is presented in several parts. The sections relevant to TSCS are stated below:

- Part 1: Asphalt Concrete (BS EN 13108-1:2016)
- Part 2: Asphalt Concrete for Very Thin Layers (*BS EN 13108-2:2016)

  **BS EN 13108-2 covers asphalt concrete surface courses with a thickness of 20 – 30 mm.*
- Part 5: Stone Mastic Asphalt (BS EN 13108-5:2016)
- Part 20: Type Testing (BS EN 13108-20:2016)
- Part 21: Factory Production Control (BS EN 13108-21:2016)

BS EN 13108-1, 2, and 5 (2016) present the framework for specifying requirements for both mixture and components. The mixture parameters and categorisation within this framework are summarised in Table 9.
The shaded cells indicate the most common parameters/categorisation across Parts 1, 2 and 5 of BS EN 13108 (2016). The allowable combinations of parameters are limited to avoid 'over specification'.

Part 20 schedules the tests (including the appropriate testing conditions, procedures and some replications) that are to be used to validate the performance of mixtures against the specification requirements that may be called up under the product standards.

Key points to note include:

- In the UK, Soft Asphalt (BS EN 13108-3:2016) and Porous Asphalt (BS EN 13108-7:2016) are not used on the SRN.
- At the time of writing, Hot Rolled Asphalts (HRA) are only permitted pavement surface course materials for new and maintenance construction if they meet the following criteria:

    - No noise 'sensitive receptors' are located within an envelope 600 m from the roadside and 600 m from the ends of the sections.
    - The scheme is not considered noise sensitive and does not have noise barriers or noise mitigation earth bunds; the location has not been identified as an Important Area, either with or without First Priority Locations as detailed in IAN 156/16.
- Alternative or proprietary materials which do not conform to the above or with non- harmonised properties must be certified by third-party accreditation bodies. This should apply to the required product performance under the combination(s) of traffic level and site classification.

Table 9 presents the allowable combinations of parameters for Asphalt Concrete (BS EN 13108 Part 1), Asphalt Concrete for Very Thin Layers (BS EN 13108 Part 2), Stone Mastic Asphalt (BS EN 13108 Part 5).

Table 9: Allowable Combinations of Parameters – BS EN 13108

Parameter	Categorisation	BS EN 13108:2016		
		Part 1	Part 2	Part 5
Grading	~	✓	✓	✓
Binder Content	B_{min}	✓	✓	✓
Void Content	V_{max}, V_{min}	V_{max}, V_{min}	V_g, V_i or V_v	V_{max}, V_{min}
Voids Filled with Bitumen	VFB_{max}, VFB_{min}	✓		✓
Voids in Mineral Aggregate	VMA_{min},	✓		
Void Content At 10 Gyrations	$V10G_{min}$	✓		
Binder Drainage	D			✓
Water Sensitivity	ITSR	✓	✓	✓
Resistance to Abrasion by Studded Tyres	AbrA	✓	✓	✓
Resistance to Permanent Deformation	P (large device) WTS_{AIR}, PRD_{AIR} (small device, procedure B)	✓		✓
Reaction to Fire	~	✓	✓	✓
Resistance to Fuel for Application on Airfields	~	✓	✓	✓
Resistance to De-Icing Fluid for Application on	B	✓	✓	✓

Airfields				
The Temperature of the Mixture	~	✓	✓	✓
Marshall Values for Application on Airfields	S_{min}, S_{max}, F, Q_{min},	✓		
Stiffness	S_{min}, S_{max}	✓		
Resistance to Permanent Deformation in Triaxial Compression Test	Fc_{max}	✓		
Resistance to Fatigue	$\varepsilon 6$	✓		
Mechanical Stability	P		✓	

3.6.2 Experience in the United Kingdom

TSCS are currently the only permitted option for a surface course on the SRN in England without specific departure approval from HE (Highways England, 2018a).

TSCS has preferable performance especially concerning reduced noise, spray and the speed of laying (Atkins, 2015). Currently, it is estimated that about 60% of the SRN in the United Kingdom has TSCS. Table 10 and Table 11 from MCHW 1 Clause 942 details the design target thickness and layer thicknesses.

Table 10: Design Target Thickness (excluding Site Categories H1, H2, L and J)

Nominal Aggregate Size (mm)	Design Target Thickness (mm)
6	20-30
10	25-40
14	35-50

Only TSCS with an upper (*D*) aggregate size of 10 mm or less are permitted on Site Categories (H1, H2, L and J). These sites are identified in the Appendix 7/1. The categories are denoted in Table 12.

Table 11: Design Target Layer Thickness for Site Categories H1, H2, L and J

Nominal Aggregate Size (mm)	Design Target Thickness (mm)
6	20-40
10	25-50

Table 12: Site Stress Level Classification

Site Category	Site Definition	Stress Level
H1	Bend (not subject to 40 mph or lower speed limit) radius 100-250 m	2
H2	Bend (not subject to 40 mph or lower speed limit) radius < 100 m	3
L	Roundabout	3
J	Approach to roundabout	4

In Clause 942, there is a mandatory requirement to carry out water sensitivity tests (BS EN 12697-12:2018) at 70% ($ITSR_{min}70$). The expected durability of TSCS has been based on the specification of the asphalt and best practice.

TSCS are expected to be laid on properly designed, well compacted and bonded pavement layers where the durability of the surface layer is not determined by bottom-up fatigue cracking (Atkins, 2015; Highways England, 2018a).

The durability of TSCS is dependent on factors that include local conditions, climate, mix design, bitumen properties, aggregate properties and traffic loading. In this context, minimum binder content is specified in MCHW Clause 942 TSCS to improve durability.

Table 13 provides the minimum design binder contents. BBTM is the French term for Asphaltic Concrete (AC) laid as a very thin asphalt surfacing.

Table 13: Minimum Design Binder Content

Minimum Target Design Binder Content*		
Maximum Aggregate Size (D)	Mixture Types: EN 13108, Parts 1 and 2 (AC & BBTM with PMB to BS EN 14023)	Mixture Types: EN 13108, Part 5 (SMA – Paving Grade Bitumen to BS EN 12591 and Fibres SMA)
14	5.0	6.0
10	5.2	6.2
6	5.4	Not Used

3.6.2.1 Scotland

Transport Scotland commissioned a desk study that identified German asphalt thin surfacing materials as a promising alternative to Clause 942 TSCS (Transport Scotland, 2015).

The potential benefits identified include superior durability, reduced noise levels, improved skid resistance, high resistance to deformation, decreased whole life costs, improved ride quality, reduced use of high friction surfaces and the reduced use of expensively imported aggregates (Transport Scotland, 2015).

Transport Scotland decided to develop the TS 2010 Surface Course Specification and Guidance (2015) based on German specifications and experience. The German SMA Mixture is a gap-graded aggregate mix utilising polymer modified bitumen and additives including fibres

(Transport Scotland, 2015). Grit is applied to the newly laid SMA surfacing material to increase the early life skid resistance (Transport Scotland, 2015).

The key parameters that distinguish the TS 2010 surfacing material from TSCS used in England include the fact that TS 2010 specifies higher binder contents, added fibres and the use of PMB.
TS 2010 has stringent requirements on mixture volumetric and Type Approval Installation Trials (TAIT). The TS 2010 specification is very prescriptive to gain initial confidence. In this context, grading of the mixed aggregates is strictly controlled. Further to this, Transport Scotland conducts annual inspections every September to assess the road conditions of the TS 2010 surfacing materials (Transport Scotland, 2015).

Binder

The binder content has a tolerance of ±0.2% (by mass) which closely controls the amount of binder in the mix (Transport Scotland, 2015). Empirical evidence from Germany highlights that high binder contents, with a close degree of control, are a fundamental requirement in ensuring the durability of an SMA mixture (ZTV Asphalt - StB, 2007). However, it should be noted that, because certain mix designs may be sensitive to binder content above a certain level, the supplier is recommended to use the lower limit of the tolerance as the start point for design purposes. TS 2010 specification requires the inclusion of fibres to act as a binder carrier to reduce binder drain off from the aggregate during production, storage and transportation (Transport Scotland, 2015).

Nominal Aggregate Size

Three nominal aggregate sizes are commonly used (0/6 mm, 0/10 mm and 0/14 mm) (Transport Scotland, 2015). The use of 0/8 mm is restricted due to a lack of industry experience in producing mixtures to this grading. 0/6 mm has been used on highly stressed areas and areas that require high skid resistance. It must be noted that contractors have had difficulties in working TS 2010 produced using 0/6 mm. This is related to challenges related to layer thicknesses and achieving a bond between surfacing and binder layers. 0/10 mm is widely used with proven performance (Transport Scotland, 2015). 0/14 mm is available but used less since 0/10 mm has proven to perform well following long term evaluation of the mechanical and performance properties of the mixtures (Atkins, 2015).

Applied Grit

Grit is used for TS 2010 materials (Transport Scotland, 2015) to provide initial skid resistance. Specifications are detailed in the guidance document. Key information includes: grit shall be free-flowing and free from agglomerations or bunching. For early life skid resistance, 2.8 mm lightly coated (1% to 1.5% bitumen content) angular grit is applied and rolled in during the second roller pass. The grit fills texture and remains on the surface with excess grit removed when the SMA has reached ambient temperature.

Surface Characteristics

Assessments on several TAIT sites have shown relatively consistent texture depth between 1.0 mm to 1.1 mm (Transport Scotland, 2015; McHale, Carswell and Roe, 2011). The grip tester is used to measure the skid resistance using the braked-wheel fixed slip device in accordance with BS 7941-2. This has been introduced as a performance requirement for the newly laid and early life condition of the material (Transport Scotland, 2015; McHale, Carswell and Roe, 2011). This has created an opportunity to adopt a more flexible approach as opposed to the specification of only Polished Stone Values (PSV) and other techniques used for the measurement of skid resistance (Transport Scotland, 2015; McHale, Carswell and Roe, 2011). An observation with the use of the TS 2010 suggests that there is more spray in comparison to Clause 942 TSCS and this has slowed down traffic although the surface dries quickly when the rain stops (McHale, Carswell and Roe, 2011).

3.6.2.2 Norfolk

Mix Design

Norfolk County Council (NCC) has used Dense SMA for more than eight years. NCC makes use of PMB with uncoated grit. The PSV of coarse aggregate is typically around 50-55. The air voids are specified to be ≤5% (Ojum et al., 2017).

Surface Characteristics

The target macro-texture is typically 0.8 mm to 1.3 mm. The material laid by NCC is considered a quiet surfacing, but experience shows that the SMA laid by NCC produces more spray in comparison to traditional TSCS which often leads to a slowing down of traffic under wet conditions (Ojum et al., 2017).

3.6.2.3 Lincolnshire

Nicholls et al., (2009) predicted that thin asphalt concrete has large variability in service from 7 years to at least 16 years. A more extreme case was reported from experience in Lincolnshire which suggests that majority of thin asphalt surfacing may require preventative treatment within 5 - 9 years of service.

Figure 6 shows the age of the TSCS when they have been treated in Lincolnshire - most sites were treated between 5 – 9 years in service as detailed in Figure 6 (Neal, 2015).

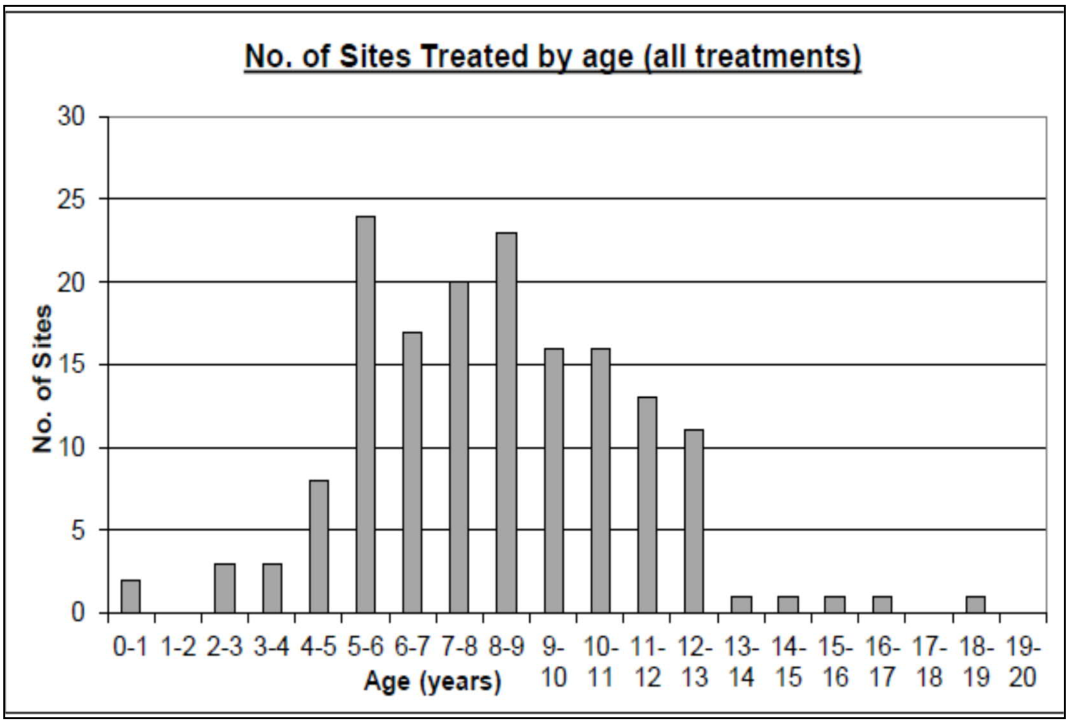

Figure 6: Number of Sites Treated at Different Age – (Neal, 2015)

3.6.2.4 Innovative Materials

Epoxy porous asphalt was trialled on A38 in Staffordshire in 1984 and 1987. It was reported that while the material on the mat area was performing well "with probable benefit to durability" (Daines, 1986; 1992).

Anecdotal feedback from Staffordshire as reported in Ojum et al., (2017) suggested that the material was highly stable but prone to mechanical damage. Following this trial, there was no follow-up of using this material on motorways until 2001 when HE was involved in a joint research project on Economic Evaluation of Long-Life Pavements. This project was a collaborative effort under the umbrella of the Organisation for Economic Co-operation and Development/European Conference of Ministers of Transport (OECD 2005; OECD, 2008).

Phase 1 of the OECD/ECMT project carried out between 2001 to 2003 identified that there were likely to be economic benefits from the development of road surfacing materials with a service life more than 30 years (Long Life Surfacing) (OECD, 2005).

The project was carried out between 2004 and 2007. This project comprised laboratory and accelerated load testing of two materials identified as having the potential to fulfil the requirement of Phase I; one of them was epoxy SMA (OECD, 2008). The benefits of epoxy asphalts include higher stiffness modulus at service temperatures as depicted in Figure 7.

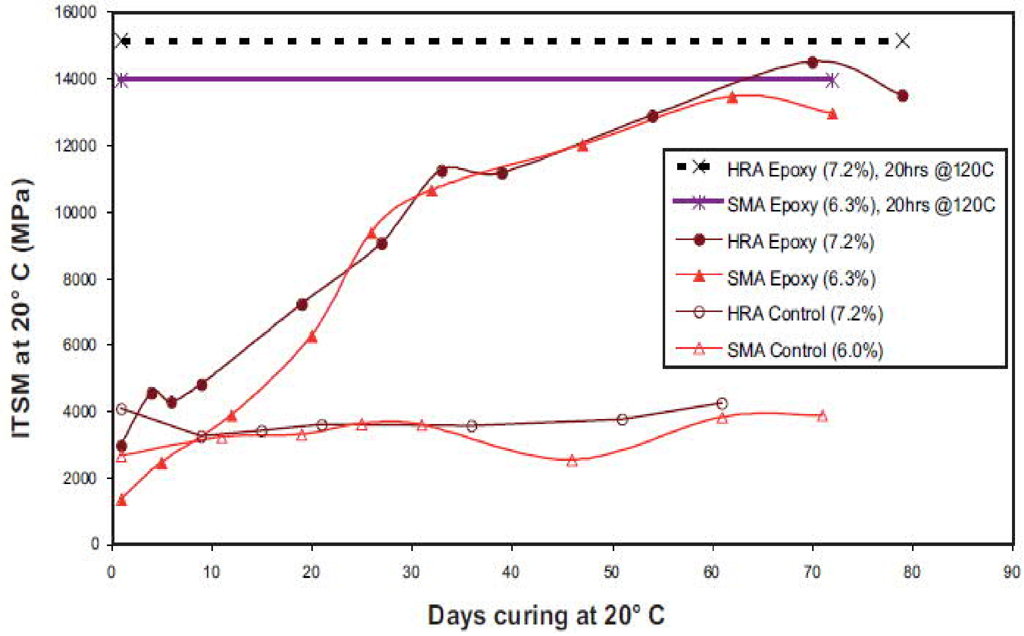

Figure 7: Stiffness Results for Hot Rolled Asphalts and Epoxy Asphalts (OECD, 2008)

A field trial on epoxy SMA was completed in January 2012 on a heavily trafficked section of the A390 Trunk Road in the South West of England as part of Phase III of the project (OECD, 2008). The trial has a long way to go before a life of 30 years can be demonstrated. Early signs monitored over 12 months in service were reported as encouraging and considered as durable and potentially long-lasting (Elliott et al., 2008; Elliott et al., 2013).

Epoxy asphalts are thermosetting which could be challenging for motorway construction. If there was a delay during delivery of the material from the mixing plant to the site beyond 2 hours after production; this could result in thermosetting of the asphalt (Elliott et al, 2008; Elliott et al, 2013). This was a concern raised during the trial on the A390 Trunk Road. At the time of writing this report, the epoxy SMA section has been reported to be in good condition, without any sign of defect (Elliott et al., 2008; Elliott et al., 2013).

3.6.2.5 Typical Onsite Condition Case Studies of TSCS in the United Kingdom taken at the 'Point of Maintenance'

- **A14-A1 Haggerston**

This site was on a single carriageway length of the A1 in Area 14 (Northumberland, Tyne & Wear, Durham and North Yorkshire). The TSCS was seven years old, and the mode of failure was severe fretting as shown in Figure 8.

A considerable amount of stripped 10 mm aggregate was found at the side of the road (Figure 9). A one-metre impermeable strip of Hot Rolled Asphalt (HRA) had been left in place with only the running lane planed and inlaid with TSCS.

Figure 8: A1 Haggerston – Site Photographs - A
(Jones and Carswell, 2012)

Figure 9: A1 Haggerston – Site Photographs - B (Jones and Carswell, 2012

Figure 10 shows a typical core obtained from the A1 Haggerston site.

Figure 10: Cores from A1 Haggerston (Jones and Carswell, 2012)

Possible Causes of Deterioration

Site observations showed that the areas of initial severe TSCS fretting were associated with cracks in the underlying layer of HRA. However, less severe fretting was also evident elsewhere along the site. There was a lot of 'stripped' 10 mm aggregate at the edge of the road. Leaving in the (impermeable) 1.0 m HRA strip at the edge of the road prevents any water in the TSCS escaping (the TSCS is laid in a 'shallow sealed dish'). This will make the surfacing more susceptible to the problems of freeze/thaw. With voids at 9.5%, it is highly probable that the TSCS will be permeable. A permeable TSCS will result in relatively rapid binder oxidation (current Penetration = 17 dmm) and allow water to get into the voids (DFT, 2006; Capita Symonds, 2007; Nicholls et al., 2009; Highways England, 2011; ADEPT, 2015). The combination of traffic and water will result in stripping of the aggregate noted from material gathered from the edge of the road. The initial severe fretting was in areas where the underlying layer of HRA was cracked. This would be expected as these areas will have relatively higher deflections. Condition data is presented in Table 14.

Table 14: Condition Data for A14-A1 Haggerston (Jones and Carswell, 2012)

Type/Name of TSCS	**PMB**	**Nominal Stone Size**	**10 mm**	**Thickness**	**28 mm**
Age	7 years	**PSV**	65	**Mode of Failure**	Fretting
Construction Layer	Single Layer of TSCS				
Voids	**Mean**	9.5		**SD**	1.5
Binder Content	**Mean**	5.2		**SD**	0.2
Binder Properties	**Pen (0.1 mm)**	16.5		**R&B (°C)**	67.4
Other Details	1 m strip of HRA left in place during construction				

- **A12 N Station Road Roundabout**

This site is a single a carriageway on A12 in Area 6 (Essex, part of Cambridgeshire, Suffolk, Peterborough & Norfolk). The TSCS was six years old, and the mode of failure was potholing and surface disintegration to the approach, departures and roundabout circulatory. This is depicted in Figure 11.

Figure 11: Fretting and Potholing on A12 N Station Road Roundabout (Jones and Carswell, 2012)

Table 15 presents the condition data for the A12 N Station Road Roundabout.

Table 15: Condition Data for A12 N Station Road Roundabout (Jones and Carswell, 2012)

Type/Name of TSCS		Nominal Stone Size		14 mm	Thickness	40 mm
Age	6 years	**PSV**	65	**Mode of Failure**		Fretting/Potholing
Construction Layer	Single Layer of TSCS on the Roundabout					
Other Details	No cores were available for this site					

Possible Causes of Deterioration

The main possible cause of deterioration could be the use of the wrong size aggregate for this site. A 14 mm size aggregate has been used on this roundabout. As this is a high-stress area, a smaller size aggregate would have created a denser TSCS which would have been more suitable for this site.

- **Area 14 – A19 Royal Quays**

This site was on a single carriageway length of the A19 in Area 14 (Northumberland, Tyne & Wear, Durham and North Yorkshire). The TSCS was eight years old, and the mode of failure was fretting as shown in Figure 12. The TSCS appears to have been constructed on 10 mm SMA binder course. The binder course was not tested but appeared, from the cores, to be highly voided (Figure 13).

Site details and TSCS test results are given in Table 16. Although there were quite extensive construction records, there was no information on the type of the TSCS.

Figure 12: A19 Royal Quays - Site Photographs
(Jones and Carswell, 2012)

Figure 13: Cores from A19 Royal Quays (Jones and Carswell, 2012)

Table 16: Condition Data for A19 Royal Quays (Jones and Carswell, 2012)

Type/Name of TSCS	Cellulose	Nominal Stone Size		10 mm	Thickness	20 mm
Age	8 years	**PSV**	65	**Mode of Failure**		Fretting
Construction Layer	TSCS Laid on Voided SMA Binder Course					
Voids	**Mean**	11.1		**SD**	1.4	
Binder Content	**Mean**	5		**SD**	N/A	
Binder Properties	**Pen (0.1 mm)**	11		**R&B (°C)**	71.8	
Other Details	White line failure as well as fretting					

Possible Causes of Deterioration

Site observations showed that the TSCS was severely fretted in the wheel paths. The TSCS was only 20 mm thick, which would normally be considered a little thin for a nominal 10 mm aggregate.

The TSCS was laid on a highly voided SMA binder course. With mean voids measured at 11.1%, the TSCS will be permeable to water. A permeable TSCS will allow air into the surfacing and will result in rapid binder oxidation (current Penetration = 11 dmm).

The combined effects of high voids, traffic loadings and a high viscosity binder could result in increased fretting in the wheel paths as noted on this site. The mean binder content was found to be 5.0%. It is not the intention to assess the compliance of the TSCS with its design as binder contents measured several years after construction would not be expected to be entirely comparable with those at manufacture. However, 5.0% would normally be a low value for a nominal 10 mm TSCS.

- **A5 Abbey Hill and Redmoor Exit and Entry Slips**

This site is a single carriageway on A5 in Area 6 (Essex, part of Cambridgeshire, Suffolk, Peterborough and Norfolk). The pavement is flexible composite. The TSCS was six years old, and the mode of failure was potholing, cracking and surface disintegration.

Figure 14: A5 Abbey Hill and Redmoor Surface Defects (Jones and Carswell, 2012)

Figure 15: A5 Abbey Hill and Redmoor Surface Defects (Jones and Carswell, 2012)

Figure 16 : A5 Abbey Hill and Redmoor with Potholing and Cracking (Jones and Carswell, 2012)

Table 17 details the construction history obtained from Highways England Pavement Management System (HAPMS) database.

Table 17: The Construction History According to the HAPMS for the A5

Material	Year	Thickness (mm)
Thin Surfacing (Generic)	03/09/2004	40
Heavy Duty Macadam	02/09/2004	50
Hot Rolled Asphalt	29/05/1974	145
Cement Bound Material	28/05/1974	100

Table 18 presents the condition data for the A5

Table 18: Condition Data for A5

Type/Name of TSCS	Generic	Nominal Stone Size	14 mm	Thickness	40 mm
Age	6 years	**PSV**	65	**Mode of Failure**	Cracking, Fretting and Potholes
Layer	40 mm TSCs and 50 mm HDM laid on a 30-year-old HRA (140 mm HRA**)**				
Other Details	White line failure as well as fretting				

<u>Possible Causes of Deterioration</u>

Site observations showed that the TSCS was severely cracked and fretting could also be observed. As the binder course was replaced at the same time as the surface course in 2004, it seems that the main issue in this site is not the underlying layer. There was no available core data to review and ascertain the binder content and air void contents.

- **Area 10 – M6 J18-19**

The cores show that the TSCS appears to have been originally constructed on a 50 mm thick layer of 20 mm binder course (MCHW Clause 929). It is likely that the binder course had replaced an existing HRA surfacing and binder course.

The photographs in Figure 17 show that the TSCS was ‘rippling’ in the wheel paths and cores taken from the wheel path in these areas of rippling showed that the TSCS to be de-bonded from the underlying binder course. Figure 17 also shows the aggregate on the underside of the de-bonded TSCS was ‘stripped’ clean of the binder.

Figure 17: Area 10 – M6 J18-19 Core and Rippling (Jones and Carswell, 2012)

The mean air void content of the TSCS is 6.8% (SD = 2.2%). At this level of air voids, the TSCS is likely to be semi-permeable. The aggregate at the bottom of the TSCS is stripped of the binder. Stripping can only take place in the presence of traffic and water, and therefore the most probable cause of the de-bonding is the effect of water and traffic at the interface possibly combined with a poor or uncured tack/bond coat.

Table 19: Condition Data for M6 J18-19

Type/Name of TSCS	PMB		Nominal Stone Size	14 mm	Thickness	35 mm
Age	6 years	**PSV**	65		**Mode of failure**	Debonding
Construction Layer	De-bonded in wheel paths - aggregate stripped on the lower face of TSCS					
Voids	**Mean**		6.8		**SD**	2.2
Binder Content	**Mean**		5.1		**SD**	N/A
Binder Properties	**Pen (0.1mm)**		34		**R&B (C)**	58.5
Other details	TSCS laid on a 50 mm binder course					

3.7 European Design Approaches

The European product standard for asphalt is mandatory and termed a harmonised standard (hEN). UK thin surfacings are proprietary materials and are required to comply with the hEN and the requirements of the European Union Construction Products Regulations (CPR) for Conformité European (CE) marking. This regime provides a significant benefit for this research as both EU countries, and those within the European Economic Area must operate within the same standards framework, which potentially facilitates the transfer of knowledge and experience.

Under Harmonised European Standards (hEN), asphalt materials for use in Europe shall fall under one of the following categories:

- EN 13108-1: Asphalt Concrete
- EN 13108-2: Asphalt Concrete for Very Thin Layers
- EN 13108-3: Soft Asphalt
- EN 13108-4: Hot Rolled Asphalt
- EN 13108-5: Stone Mastic Asphalt
- EN 13108-6: Mastic Asphalt
- EN 13108-7: Porous Asphalt
- EN 13108-9: Ultra-Thin Layer Asphalt Concrete

3.7.1 France

The procedure used in France for the design of bituminous mixtures is documented in "LPC Bituminous Mixtures Design Guide". This document focuses on the development of an initial mix formulation which is subjected to a testing regime which increases in testing requirements dependent on: the position within the pavement, i.e. surface course, base course or base stress level of 'technical' risk. The regime may be summarised as detailed in Table 20.

Table 20: French Design Test Requirements

Mixture Design Level	Testing Requirements
0	Initial mixture formulation
1	Water sensitivity, void content
2	Water sensitivity, void content, deformation resistance
3	Water sensitivity, void content, deformation resistance, stiffness
4	Water sensitivity, void content, deformation resistance, stiffness, fatigue

This incremental approach illustrates the fundamental importance of water sensitivity and void content on mixture performance (Atkins, 2015). This is reflected in the specification requirements for bituminous mixtures used in France, documented by Service d'Etudes Techniques des Routes et Autoroutes (SETRA, 2008).

This document shows that water sensitivity (retained indirect tensile strength - ITSR) and void content (V_{max}, V_{min}) criteria are stipulated for all mixture formulations and applications (SETRA, 2008). France has similar classifications as the UK on asphalt surfacing specifically: thin Asphalt Concrete, Very Thin Asphalt Concrete (VTLAC) and Ultra-Thin Asphalt Concrete (UTAC).

These materials are typically gap graded with 0/10 mm or 0/6 mm nominal size aggregate with options to adapt continuously graded mixtures. The shift is to “optimise” the mix design towards denser gap-graded mixtures with aggregate gradation between continuously graded Grave Bitumè (GB2) and gap-graded SMA as shown by the High-Performance Asphalts (HPA) materials in Figure 18 (Olard, 2012).

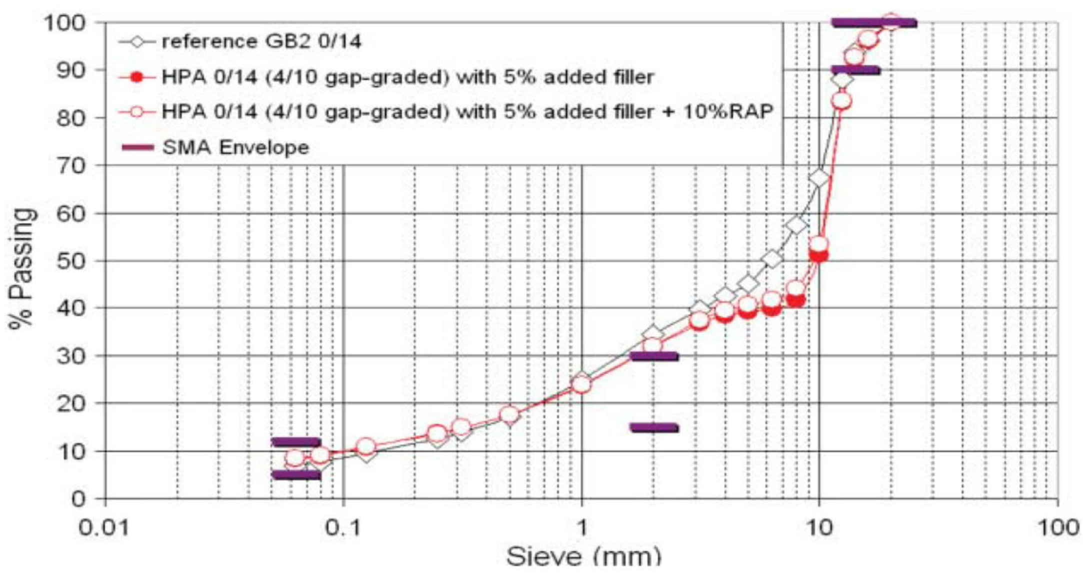

Figure 18: Grading of Optimised Mix Designs (Olard, 2012)

Mix Design

Overall the mix design methodology is based on component characteristics, water-sensitivity testing, void content assessments using gyratory compaction, resistance to permanent deformation, stiffness and fatigue resistance. In practice this methodology has adopted two approaches: "empirical" and "fundamental":

- The empirical approach contains a recipe part (to a rather considerable extent), a volumetric part and an empirical testing part. Where applicable, performance related tests are used.
- The fundamental approach encompasses a reduced prescriptive part, a volumetric part and performance-related tests.

Surface Characteristics

For surface characteristics, the emphasis is placed on durable mixtures with high resistance to water action and resistance to permanent deformation. Other factors include angular shaped aggregates for adequate skid resistance and reduced rolling noise. Minimum PSV value specified is 50. Paving grade bitumen 50/70 or 35/50 or polymer modified bitumen 45/80-60 or 40/100-65 is typically specified at a minimum binder content of 5%. There is no target macro-texture, but continuous friction measurement equipment (SCRIM type) is used to monitor skid resistance.

Construction and Experience

In-situ void measurements are usually measured using the gamma densitometer to check compliance with standard based specifications. The use of 6 mm aggregate had better skid resistance than 34,500 pavements with 10 mm aggregates. Although, it must be noted that the use of 10 mm aggregates resulted in improved surface draining and reduced spray in comparison to 6 mm aggregates. Sand grit is used as part of the process for constructing asphalt surfacings.

3.7.2 Norway

The Norwegian Public Roads Administration (NPRA) is faced with unique challenges due to the cold winter climate (Atkins, 2015). Significant ground movements occur due to freeze-thaw cycles. Roads need to be designed considering the impact of studded tyres used by most motorists. NPRA prohibits resurfacing and new construction for surface courses between September and May (Atkins, 2015).

The SMA’s used in Norway are recipe based and detailed in (NPRA, 2014). For main roads (highways) this is a 45 mm thick layer of 16 mm aggregate material. Target void content of between 2% and 4.5%.

The main deterioration mechanism in Norway is rutting. This is attributed to a higher deterioration rate for the pavement under wet conditions, or it may be due to the severity of freeze-thaw cycles which typically will be more severe in moist environments for given temperatures (Hjelle, 2007).

A five-year warranty period applies, and this is supported by a system of annual inspections undertaken jointly by the NRA with its contractors. Detailed construction records for all materials used on their network are stored in a national database which is independent of the pavement management system (NPRA, 2014; Atkins, 2015).

3.7.3 Netherlands

Twin-layered porous asphalt is the preferred surfacing option on the SRN in the Netherlands. This is based on noise considerations. Typically, a 6 mm aggregate is used in the surface layer with a 16 mm sized aggregate used in the lower layer. Respective layer depths are typically 20 mm and 50 mm. The pavement is constructed in two separate layers (i.e. not a twin paver) (Morgan et al., 2010).

No bond coat is used between the layers. Adhesion is instead provided by “Hot on Warm” approach. There is no specification requirement or measurement of texture depth. In service, the noise benefits only last for two or three years. Clogging of the pores is not regarded as a problem and cleaning is seldom undertaken.

Ravelling is the main defect that manifests itself at the surface. Bitumen emulsion rejuvenators are sometimes applied as a preventative measure and can extend the life of the surface course by a couple of extra years. The twin porous surface course is replaced at the end of its serviceable life (Morgan et al., 2010).

3.8 Use of Asphalt Surfacing Materials Worldwide

3.8.1 United States

The Strategic Highway Research Program (SHRP, 1994) developed the Superpave (Superior Performing Asphalt Pavements) design which is based on performance specifications.

The Superpave system combines asphalt binder and aggregate selection into the mix design process and considers traffic and climatic conditions. The compaction devices from the Hveem and Marshall procedures have been replaced by the gyratory compactor.

The Superpave mix design procedure comprises of steps that include aggregate selection, binder selection, sample preparation including compaction, performance testing, density and voids calculations. Other steps include optimum binder content selection and evaluation of moisture susceptibility.

Aggregate Selection

The aggregate structure acts as the skeleton of the mixture and influences skid resistance, stability and workability. The Superpave design method restricts control points for the gradation placing restrictions on angularity of the coarse, fine aggregates and the clay content as seen in Figure 19.

The major point here is to promote optimum interlocking properties in the aggregate structure and accommodate appropriate binder and void contents.

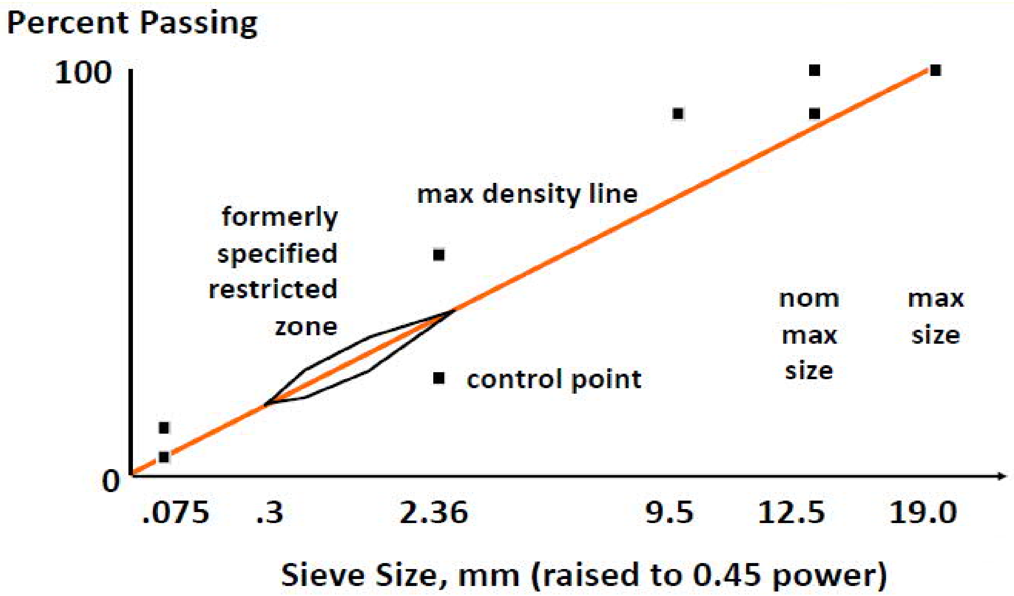

Figure 19: Aggregate Gradation Factors

Coarse aggregate angularity is ascertained using any number of test procedures that are designed to determine the percentage of fractured faces such as the flakiness and elongation tests. The fine aggregate angularity and the sand equivalent test to determine clay content are shown in Figure 20.

Figure 20 shows the Superpave coarse aggregate angularity requirements. The fine aggregate and sand equivalent requirements are detailed in the Superpave asphalt mix design procedure.

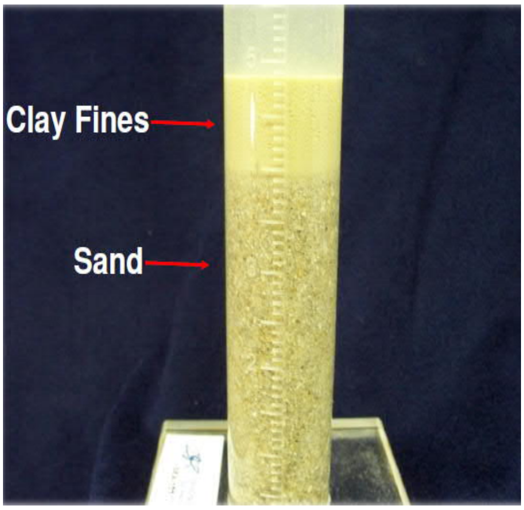

Figure 20: Fine Aggregate Angularity and Sand Equivalent Tests

Table 21: Fine Aggregate Angularity and Sand Equivalent Tests

Design Traffic Level	ESAL's	% Crushed 1-FF/2-FF ≤ 100 mm	% Crushed 1-FF/2-FF > 100 mm
F	< 300,000	55/-	-/-
E	300,000 to < 3,000,000	75/-	50/-
D	3,000,000 to < 10,000,000	85/80	60/-
C	10,000,000 to < 30,000,000	95/90	80/75
B	≥ 30,000,000	100/100	100/100

Binder Selection

Superpave introduced the performance grading (PG) system which is based on the expected pavement temperature. The Superpave mix design method determines both a high temperature which is based on the 7-day maximum pavement temperature and a low design temperature based on the minimum pavement temperature. A typical Superpave binder specification is shown below in Figure 21. The Multiple Stress Creep Recovery (MSCR) test is the latest improvement to the Superpave binder specification. This provides a new high-temperature binder specification that more accurately shows the rutting performance of the binder.

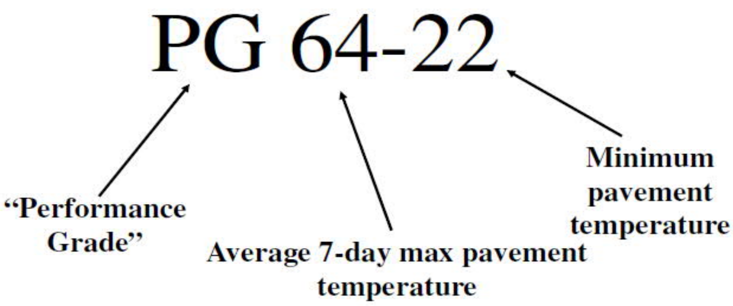

Figure 21: Example of Superpave Binder Specification

Mix Design

Trial blends are established, and the best blend that meets all compaction and mixture requirement is selected. 4% is the design air voids and dust/effective binder ratio is between 0.6 and 1.6.

Construction and Experience

May (1996) summarised the major difficulties during construction of Superpave to include obtaining the specified density, meeting VMA requirements, segregation of coarse-graded mixes, shoving under the intermediate roller and sticking of mix to truck beds. With Superpave, the most often heard remark and concerns from experience are the difficulties with obtaining the specified density. This is controlled by ensuring that the mix is mixed, compacted and placed at the correct temperatures.

The use of material transfer vehicles such as the shuttle buggy and temperature sensors assist in ensuring the asphalt material is laid correctly and to the right temperature. Much of the observed cracking on Superpave especially load cracking appears to be related to construction issues (Watson, 2003).

3.8.2 South Africa

South Africa’s (SA) road network comprises national, provincial and local systems. A significant portion of the surfaced roads has asphalt as part of their pavement structure used in a variety of traffic loading and environmental conditions.

Typical SA pavements comprise of thin asphalt surfacing course systems (<40 mm thick) overlaying a granular base layer (Smith and Visser, 2008; Road Agency, 2013; Anochie-Boateng et al., 2015).

Binder Selection

The type of binder is selected based on the following factors that include; traffic, climate, failure modes, pavement structure and availability of binder and aggregate types. Current developments mean SA is transitioning towards performance-related specifications.

Mix Design

Key materials for thin asphalt surface comprise of high quality single sized road stone, fine crushed dust, unmodified paving grade bitumen (40/50 or 60/70 depending on the environment) and a low lime content to act as a filler and adhesive agent.

In some instances, an anti-stripping agent is used in the mixture to enhance the adhesion of the binder to potentially problematic aggregate. Experience has shown that it has not yet been necessary to modify the bitumen used in the asphalt.

Failure Mechanisms

Typical failure mechanisms experienced on SA roads usually occur as a combination of the following factors; ravelling, permanent deformation, cracking and loss of surface texture. Other factors include stripping, disintegration of the layer and bleeding of the asphalt surface.

Ravelling of the pavement has been identified as the most probable failure mode to be expected with disintegration progressing from the surface downwards. Permanent deformation at slow-moving or stationary traffic loading conditions is evident. This is attributed to the rise in high tonnage trucks and increasing traffic volume. High pavement temperatures, especially in summer which could easily exceed 40°C is another factor that could result in binder flow. With respect to tackling the failure mechanisms, the influence of void content on the permeability of thin asphalt surfacing layers is significant, and it is advised that a density study is undertaken on projects where the permeability of the asphalt layer is critical. With respect to moisture susceptibility, Table 22 shows typical mix additives added to help with tackling moisture susceptibility on SA roads based on the tensile strength ratio. The addition of 1% lime as an active filler had the best results and even better when the lime was injected in the drum with the bitumen.

Table 22: Moisture Susceptibility on South African Roads (Liebenberg et al., 2004)

Mix additives or active filler	Moisture susceptibility result (Laboratory prepared mixes)
No additives, no active filler	58,7 % 48,2 %
Polyamine added, no active filler	46,4 % 48,2 %
No additives, no active fillers, High P0,075 (P0,075 mm > 10)	3,2%
1% cement as active filler	41,9 %
1% lime as active filler	75,0 %
2% lime as active filler	50,5 %
	Moisture susceptibility result (Plant mixes)
No additives, no active filler	47,0 %
1% lime added – mixed with sand	52,9 %
1% lime added – injected in drum with bitumen	77,1 %

Construction

The Marshall method is widely used in designing asphalt layers in SA. However, there are two different approaches in producing the mixtures (Marshall or Gyratory) depending on the region. SA makes use of rolled in chips, but this has been found to have a negative effect on the permeability of the thin asphalt layer. The expected life is between 8-12 years depending on traffic.

Model Mobile Load Simulator (MMLS3)

The use of the Model Mobile Load Simulator (MMLS3) as an accelerated pavement tester continues to garner worldwide attention. A protocol guideline method for evaluation of permanent deformation and susceptibility to moisture damage using the MMLS3 has been drafted by SANRAL (South African National Roads Agency SOC Limited).

Key challenges and areas for more detailed focus include vehicle-pavement interaction and environment-pavement interaction. Further work is needed to improve Mechanistic-Empirical Pavement Design Guide (MEPDG) validation and improve reliability in pavement design while using the MMLS3.

Challenges

In recent correspondence with Herman Wolff (AECOM Executive for South Africa Office), a major challenge is the ability to manufacture asphalts with a high modulus of elasticity and a high strain at break (SABITA, 2014).

This requirement is to facilitate good load distribution and rutting resistance characteristics due to the high modulus of elasticity, while the high strain break will improve the fatigue properties on pavements with relatively high elastic deflections under load applications.

3.8.3 New Zealand

In recent times, New Zealand has installed trials of Epoxy-Modified Open Graded Porous Asphalts (EMOGPA) on the Christchurch Southern Motorway for use as a thin surface layer.

Epoxy Asphalt is a premium material widely used in bridge decking solutions as opposed to road pavement surfacing due to cost implications (OECD, 2008). Epoxies are thermosetting materials that are hard and rigid after curing. These materials are two-part systems that result from the reaction of a curing agent (Part A) and a bitumen/resin component (Part B) as seen in Figure 22.

Construction

Production experience to date for the relatively small quantities used has almost exclusively been with a batch plant that gives good control of mixing time. Mixing time is an important parameter due to the thermosetting nature of the material. Extra care is required in the timing of the manufacturing and construction phases to ensure the product is not under or over cured at compaction.

In 2007, Transport New Zealand installed several trial sections on Main North Road in Christchurch comprising a standard Porous Asphalt and EMOGPA with 20% and 30% design air voids. Observations during construction included roller pickup and the EMOGPA surfacing being “lively” within 3 hours of compaction. However, satisfactory performance was recorded during the assessment of the EMOGPA sections in 2010.

Figure 22: The Two-Component System of Epoxy Asphalts (OECD/ITF 2008)

The use of a continuous mix drum plant is also feasible to produce epoxy asphalts. This has been used in New Zealand with no issues although further research and investigation has been highlighted concerning optimising the curing profile with the desired rate of reaction for local conditions. This includes time for curing, transportation and laying characteristics.

Benefits

Epoxy asphalts are not considered to be susceptible to moisture damage. There was a higher resistance to oxidative degradation at ambient temperatures; improved resistance to rutting, improved resistance to fatigue cracking although the benefits were marginal at high strain levels. Epoxy asphalt was more resistant to surface abrasion and loss of materials from tyre action even after oxidation as seen in Figure 23. Some epoxy systems have shown the ability to cure rapidly at a lower temperature than might be expected. To summarise, test performance indicates that the use of epoxy asphalts outperforms conventional mixtures providing a surfacing material with a maintenance life of more than 30 years if all the aspects of the process are correctly handled (OECD/ITF 2008).

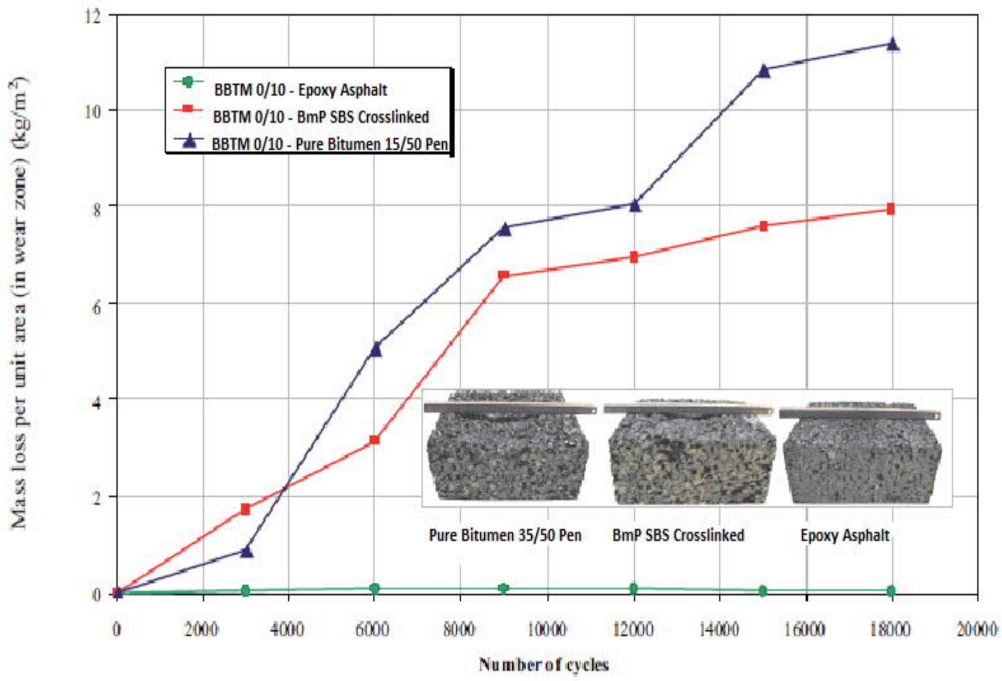

Figure 23: Evolution of Mass Loss

3.9 Conclusion

This chapter reviewed TSCS used worldwide considering the mix designs, surface characteristics, construction issues and observed experience. The conclusions and key factors from this review are:

1. Poor compaction results in high air void contents. The literature review shows the importance of design and in situ void content to achieve long term mechanical and performance properties.
2. Despite some perceptions to the contrary, the service lives that are achieved for TSCS in the UK compare favourably with those that are experienced overseas.
3. The use of PMB's in Europe is widespread.
4. The current UK specification for TSCS does not include any specific requirements for the inclusion of a PMB nor is there any clear guidance on the benefits which different types of polymers are expected to impart.

5. Prolonged wet weather and severe winters could influence the condition of thin surfacing on the UK trunk road network. European counterparts reported similar challenges.

The information from this review is summarised below in Table 23.

Table 23: Summary of Design Parameters and Approaches Worldwide

Country	Asphalt	Grading	Binder Type	Binder Content	Air Voids	Skid Resistance	Failure Modes
France	VTLAC, UTAC	0/6 mm and 0/10 mm	Performance Grade	Target 5%	V_{max}, V_{min}	No target (SCRIM)	Water Sensitivity; Deformation; Fatigue
Norway	N/A	16 mm	N/A	N/A	Target 2.0 - 4.5%	N/A	Studded Tyres Impact; Rutting;
Netherlands	Twin Porous Asphalt	6 mm (upper) 16 mm (lower)	N/A	N/A	N/A	N/A	Ravelling
United States	N/A	Aggregate, angularity and clay content	Performance Grade	Dust/effective binder ratio	Target 4.0%	N/A	N/A
South Africa	N/A	Single size, fine dust	Performance Grade	N/A	N/A	N/A	Ravelling; Water Sensitivity
Scotland	TS 2010	Gap-graded; 0/6, 0/10, 0/14 mm	PMB	Higher than TSCS	N/A	1.0-1.1 mm	N/A
England	TSCS	Gap-graded; 0/6 mm, 0/10 mm, 0/14 mm	PG 40/60 or PMB	Based on Aggregate Size	V_{max}, V_{min}	Texture depth and skid resistance	Fretting; Water Sensitivity

4. LITERATURE REVIEW OF VISCOUS TO ELASTIC TRANSITION (VET) TEMPERATURES

4.1 Introduction

This chapter introduces the concept of Viscous to Elastic Transition (VET) temperature analysis and provides discussions on its application for use in evaluating the performance of TSCS. Findings and concepts on the use of VET analysis are presented, considering experiences in France, the United Kingdom and the United States.

4.2 Viscoelastic Properties of Bituminous Materials

Viscoelastic properties of bituminous materials are mostly characterised by two important factors: the complex modulus (G*) and the phase angle (δ). The complex modulus provides information on the stiffness properties of the binder. This parameter indicates the resistance of the binder to deform under a given set of loading conditions which includes the elastic and viscous (loss) moduli while the phase angle represents the viscoelastic response (Anderson et al., 1994).

There are various key functions used to evaluate the viscoelastic response and behaviour of bitumen. These include the complex modulus as a function of loading frequency, creep modulus as a function of loading time and Newtonian viscosity as a function of temperature (Widyatmoko et al., 2004). Bitumen at a slow rate of loading, or at long loading time, or at high temperatures will exhibit viscous behaviour and on the other hand, at a rapid rate of loading, or at short loading time, or at low temperatures, the bitumen shows elastic behaviour (Anderson et al., 1994). High phase angles show a propensity for the binder to become viscous liquid and susceptible to flow, while lower phase angles indicate more elastic response which is

often associated with high stiffness and possibly increased brittleness (Anderson et al., 1994; Airey, 2004; Widyatmoko et al., 2004).
An understanding of these key viscoelastic behaviours is fundamental and essential for this study due to the significant influence these properties have on crack resistance of the produced bituminous mixtures.

This can be assessed further by evaluating their transitional (viscoelastic) properties from the elastic-solid state to the viscous-liquid state (or vice versa), under a loading arrangement and temperature condition (Widyatmoko et al., 2004).

In the United Kingdom (UK), the Dynamic Shear Rheometer (DSR) is widely used to ascertain the rheological and dynamic mechanical properties of bitumen. The use of DSR is specified in the Manual of Contract Documents for Highway Works Clause 956 (2018), and the test is performed to BS EN 14770.

4.3 Ageing of Bitumen

Ageing results in hardening of bituminous binders (Apeagyei, 2017). Age hardening of bitumen takes place during asphalt production, transportation, during laying and paving operations of the asphalt (Read and Whiteoak, 2003). Subsequent age hardening occurs at ambient temperatures over the serviceable life of the pavement (Said, 2005). It should be noted that the initial hardening of the asphalt immediately after paving is essential to improve the stiffness and load spreading ability of the pavement. However, excessive hardening during the serviceable life of the pavement can limit the flexibility and reduce the capacity for the binder to recover and heal after loading; this may lead to embrittlement and increased susceptibility to cracking. Furthermore, any presence of moisture may further increase the risk of failure, especially in high stiffness modulus asphalts (Widyatmoko et al., 2004).

4.4 Resistance to Cracking of Bitumen

Fretting is the progressive disintegration of TSCS due to the loss and dislodgement of aggregate particles from the asphalt matrix (Alabaster et al., 2015). It occurs when individual aggregate particles are lost under the action of traffic and environmental factors resulting in crack initiation and propagation (Alabaster et al., 2015).

Cracking is a main failure mechanism of asphalt mixtures predominantly influenced by the properties of the binder in the mixture (Widyatmoko et al., 2004). This type of failure is mostly found under low to intermediate service temperatures, although high-temperature cracking can take place in desert regions where asphalt can be substantially age-hardened. Low temperature cracking is predominantly caused by thermal variations in the material, while intermediate temperature cracking can be caused by combinations of thermal and load/fatigue associated cracking (Widyatmoko et al., 2004). Binder cracking if interconnected will be manifested in the asphalt mixture as transverse, longitudinal or a mixture of these cracks) while unconnected cracks may result in material loss leading to fretting, potential loss of stiffness and load spreading ability.

4.4.1 Low Temperature Cracking

At low temperatures, bitumen behaviour will be predominantly linear-elastic, and the lack of viscous behaviour makes the bitumen prone to cracking. Empirically, binder resistance against low temperature cracking has been characterised by Fraass breaking value where a thin bitumen film will be flexed and bent at low temperatures until the bitumen cracks. This parameter is widely adopted in Europe and included in the current bitumen grading systems such as EN 12591 and EN 14023. In the US, however, a more fundamental approach was adopted in the Superpave binder grading system (AASHTO M320), where critical parameters will be determined using Bending Beam Rheometer (BBR) and Direct Tension (DT) tests.

4.4.2 Intermediate Temperature Cracking

At intermediate temperatures, bitumen behaviour is expected to be within the linear viscoelastic range where any deformation can potentially be recoverable (Widyatmoko et al., 2004). However, cracks can take place when the bitumen has substantially aged and been subjected to loading beyond its capacity. Some variants of ductility tests have been adopted in Europe as parameters for intermediate temperature cracking. The Superpave specification (AASHTO M320, 2016) uses rheological data to derive G* x sin δ, which is specified at a temperature related to the high and low Performance Grade (PG) temperatures in that specification. However, recent studies and research have simplified rheological parameters which are deemed more closely related to cracking (Widyatmoko et al., 2004; Rowe, 2014). These new parameters include G^*_{VET}, T_{VET} and G-R. For the reasonably moderate climatic condition in the UK, asphalt cracking is considered to fall within the category “intermediate temperatures”. Consequently, the following discussions will focus on parameters at the intermediate service temperatures.

4.5 Viscous to Elastic Transition Temperature

The Viscous to Elastic Transition (VET) temperature, T_{VET}, has been defined as the temperature at a phase angle value of 45 degrees at which the elastic component of the complex shear (stiffness) modulus, G’, of a bituminous material equates to the viscous component, G”, (hence G’ = G” at T_{VET}) (Widyatmoko et al., 2005). Therefore, the viscoelastic response of bitumen at this temperature will be considered at equilibrium where neither elastic nor viscous elements will dominate the response. As described previously, any increase in elastic response is often associated with reduced flexibility, and possibly reduced resistance to cracking. In this context, any increase in T_{VET} may be associated with increasing the risk for cracking to occur at a higher temperature. The concepts of correlating VET analysis to site conditions are presented in this section.

4.5.1 Experience from France

Migliori et al., (1999) presented comprehensive studies on the rheological properties of bitumen obtained from selected sites in France after a traffic period of 7 years. These sites comprised asphalt concrete incorporating paving grade bitumen using either 35/50 or 50/70; it was reported that cracks were mainly found on sites incorporating paving grade bitumen 35/50. DSR testing was carried out at 7.8 Hz, and the results showed strong correlations between the T_{VET} and the observed surface conditions (with and without cracking), with correlation coefficients (r) reported to range between 0.8 and 0.9. The correlations provided by Migliori et al., (1999) present a basis for ascertaining critical levels against the observed surface cracking for the studied asphalt concrete, as shown below:

- T_{VET} (7.8 Hz) for a site more than seven years old must not be greater than 35°C.
- Increase in T_{VET} (7.8 Hz) for site sample must not be greater than 13°C of the initial value.

4.5.2 Experience from the United Kingdom

Following Migliori's work, the complex modulus at the VET temperature termed G^*_{VET} was introduced during a series of laboratory assessments on the ageing characteristics of paving grade bitumen obtained from different sources by Widyatmoko et al., (2004) and the subsequent assessment of samples removed from distress and non-distress area (Widyatmoko, 2005).

4.5.2.1 Case Study A

Widyatmoko et al., (2002) conducted tests on 50 pen and 15 pen bitumen using the DSR to assess the effect of age-hardening and bitumen production method in VET analysis. Specifically, the test encompassed the following:
Three bitumen conditions were considered to assess age-hardening:

- As received (unaged) bitumen;
- Laboratory short-term aged bitumen, after Rolling Thin Film Oven Test (RTFOT); and,
- Long-term aged bitumen, after conditioning using the High-Pressure Ageing Test (HiPAT)

RTFOT simulates ageing during the mixing, transportation and laying process while HiPAT simulates ageing which occurs during the serviceable life of the bitumen. Two bitumen production methods, specifically semi-blown and straight-run (distilled to grade) were used.

The selected samples are identified as:

A. 50 pen, semi-blown bitumen.
B. 15 pen, semi-blown bitumen (Sample A).
C. 15 pen, semi-blown bitumen (Sample B).
D. 15 pen, straight-run bitumen.

Figure 24 shows the plot of the G* at VET Temperature in comparison to the T_{VET} for the samples tested at 0.4 Hz.

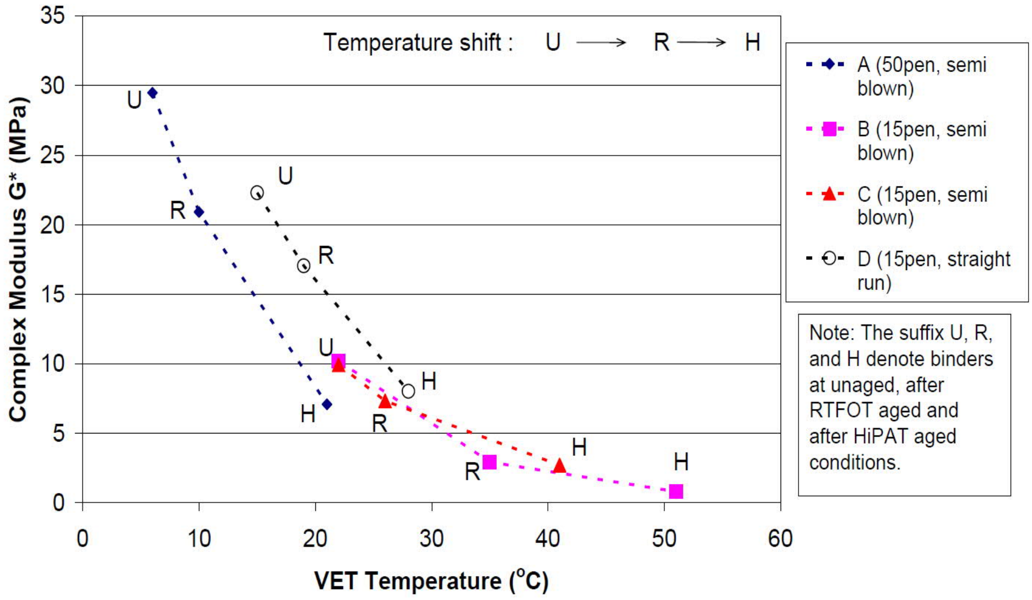

Figure 24: Case A - Complex Modulus vs the VET Temperature (Widyatmoko et al., 2005)

Figure 24 shows that the VET temperatures are dependent on age condition, production method and grade of the binder. The results demonstrated that:

- As the level of age hardening increased from the unaged to the RTFOT and to the HiPAT, for the samples tested, the T_{VET} increased. Further to this, it was noted that as the T_{VET} increased, the G^*_{VET} decreased.
- Both 15 pen semi-blown bitumen showed similar test results, while the 15 pen straight-run showed reduced T_{VET} and higher G^*_{VET}.
- For semi-blown bitumen, the softer 50 pen showed reduced T_{VET} and higher G^*_{VET} than the harder 15 pen.

4.5.2.2 Case Study B

Further assessments using DSR at 0.4 Hz were conducted by Widyatmoko et al., (2004, 2005) on binder recovered from Stone Mastic Asphalt cores comprising bitumen with 50 pen (SMA 50) obtained from four sites in England. It was understood that these samples were manufactured using bitumen from the same supplier, and therefore the bitumen production method or source was expected to be the same.

It was reported that these samples were obtained from good (No Crack) and bad (Crack) sites that had been in service and trafficked for no more than three years. Data from ‘the Control’ bitumen with initial penetrations of 42 and 53 dmm, after RTFOT and after HiPAT, were also presented for comparison; these results are plotted in Figure 25.

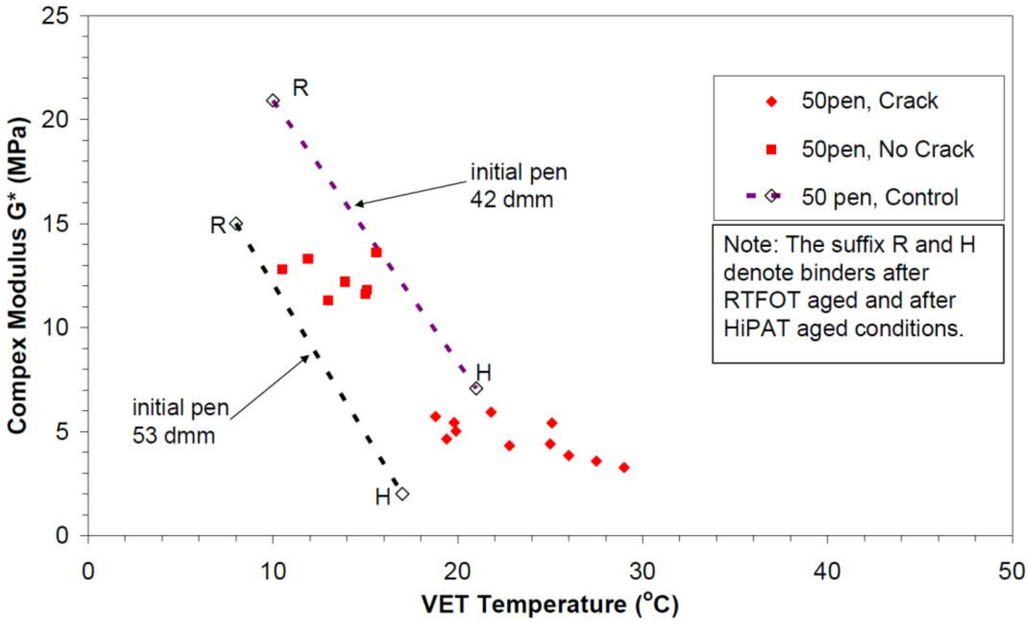

Figure 25: Case B - Complex Modulus vs the VET Temperature (Widyatmoko et al., 2005)

The test results presented in Figure 25 show that the sites with and without cracking formed two distinctive groups when plotted in a graph of the complex modulus (G^*_{VET}) versus the T_{VET}.

Figure 25 shows increased T_{VET} and much reduced G^*_{VET} for the cracked 50 pen sections indicating poor site conditions. In contrast, results from the good sites with no evidence of cracks show lower T_{VET} and higher G^*_{VET} values. This trend complements the findings detailed in Case Study A where a reduction in crack resistance can also occur on relatively new materials (less than three years old), even though they were manufactured with bitumen of the same grade and production method.

As demonstrated in the study, the T_{VET} was found to be capable of distinguishing between good sites and poor sites. A reduction of G^*_{VET} indicates reduced load-spreading capacity: G^*_{VET} (good sites) > G^*_{VET} (poor sites). The evidence from laboratory-produced samples and samples obtained from the site show that there is a strong correlation between analyses using T_{VET} and observed surface cracking on sites.

Recommendations from the above studies (Widyatmoko et al., 2004, 2005) stated that to minimise the risk of cracking in asphalt surface course comprising 50 pen bitumen; the following parameters should be considered together:

T_{VET} (0.4Hz) < 20°C <u>and</u> G^*_{VET} (0.4 Hz) > 10 MPa.

4.5.3 Experience from the United States

There are various analytical models and assessment tools used in ascertaining the performance of binders. The Christensen-Anderson (CA) model is a very useful tool used in characterising the relationship between stiffness expressed as complex modulus (*G**) or bending stiffness *S (t)*) and loading time expressed as frequency or time of loading (Christensen and Anderson, 1992; Anderson et al., 1994). The G* equation for the CA model is detailed below:

$$G^* = G_g[1 + \left({}^{\omega}/_{\omega_c}\right)^{log2/R}]^{-R}/_{log2}$$

The key parameters comprise:

- The glassy modulus, G_g which represents the upper limit of the modulus at very high frequencies and low temperatures.

- The crossover frequency, ω_c, determines the location of R on the master curve.
- The rheological index, R, characterises the shape of the master curve and equates to the difference between the glassy modulus and the modulus at the crossover frequency.

As detailed by Christensen et al., (2017), the CA model was further developed by Marasteanu and Anderson (1999). This modified version of the CA model is commonly referred to as the CAM model.

The CAM model provides greater flexibility in the rate at which the phase angle approaches the viscous flow and glassy modulus. The G* equation for the CAM model is detailed below:

$$G^* = G_g[1 + \left({}^{\omega}/_{\omega_c}\right)^v]^{w/v}$$

Figure 26 shows the key parameters for the CA/CAM models.

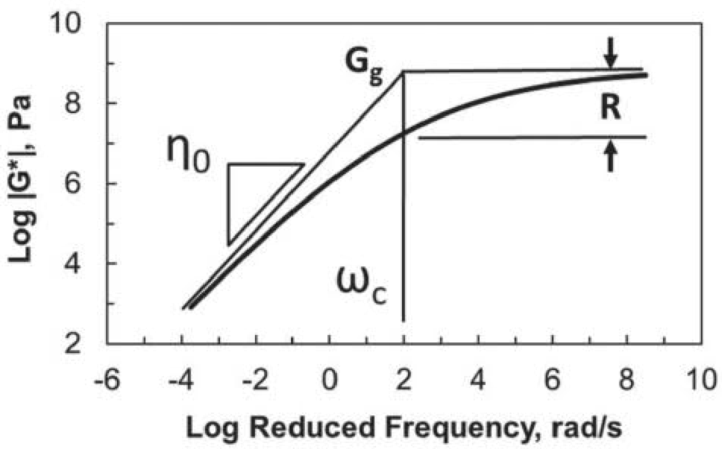

Figure 26: Key Parameters for the CA/CAM Models (Christensen et al., 2017)

The Glover-Rowe (G-R) parameter is another model developed to understand the performance of binders and assess resistance to cracking (Rowe, 2014). The model is detailed below:

$$G - R = \frac{G^*(cos\delta)^2}{\sin\delta}$$

As detailed by Rowe (2014), the resulting parameter from the equation is dependent on *G** and δ measured in the linear region. The two suggested criteria and applications are as detailed below:

$$Damage\ Onset:\ G^{*}((cos\delta)^{2}/sin\ \delta) = 180\ kPa$$
$$Significant\ Cracking:\ G^{*}((cos\delta)^{2}/sin\ \delta) = 450\ kPa$$

Figure 27 depicts the G-R model showing the potential onset of cracking and areas with potential for significant cracking as a factor of ageing on the binder considering the equations above.

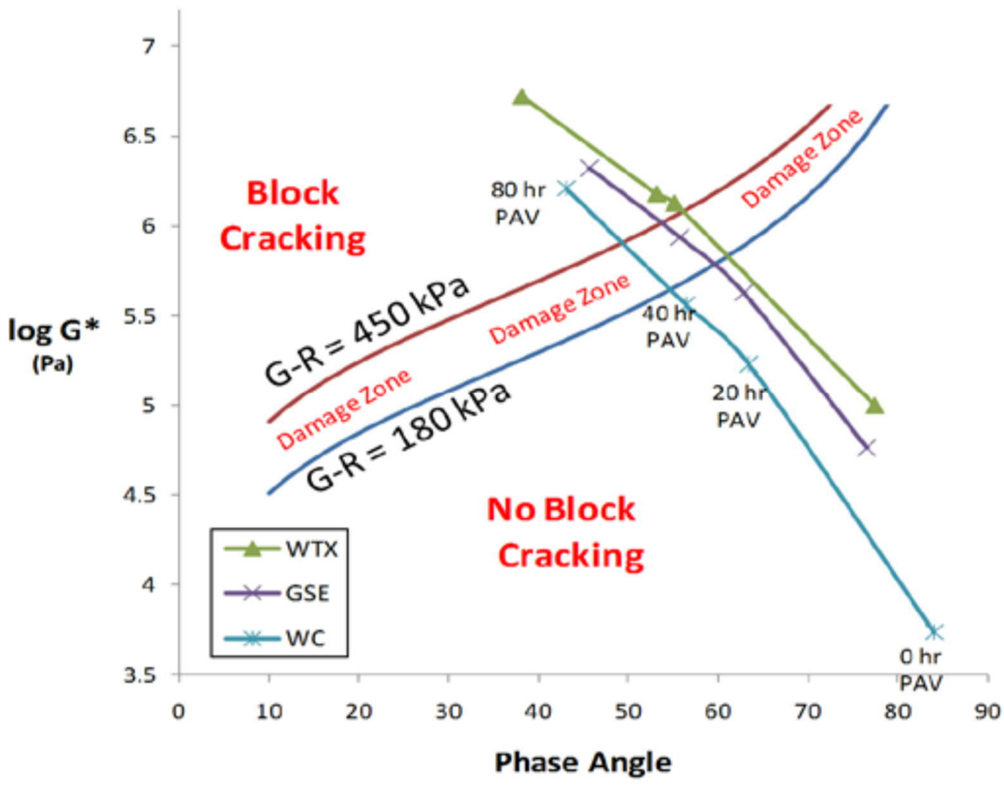

Figure 27: G-R Model (Rowe, 2014)

King et al., (2013) and Rowe et al., (2014) used the G-R model computed at 15°C and 0.005 rads/sec to analyse *G** and δ data from a project at Newark Airport where early life cracking was identified.

Figure 28 presents the test results showing G* vs δ. The test results indicate that the PG 76-28 and the PG 82-22 showed signs of damage and potential for significant cracking in accordance with principles as detailed in the G-R equations above. This was reflected from site observations showing that the modified PG 76-28 and the PG 82-22 had durability issues in comparison to the conventional PG 64-22 which performed with no issues.

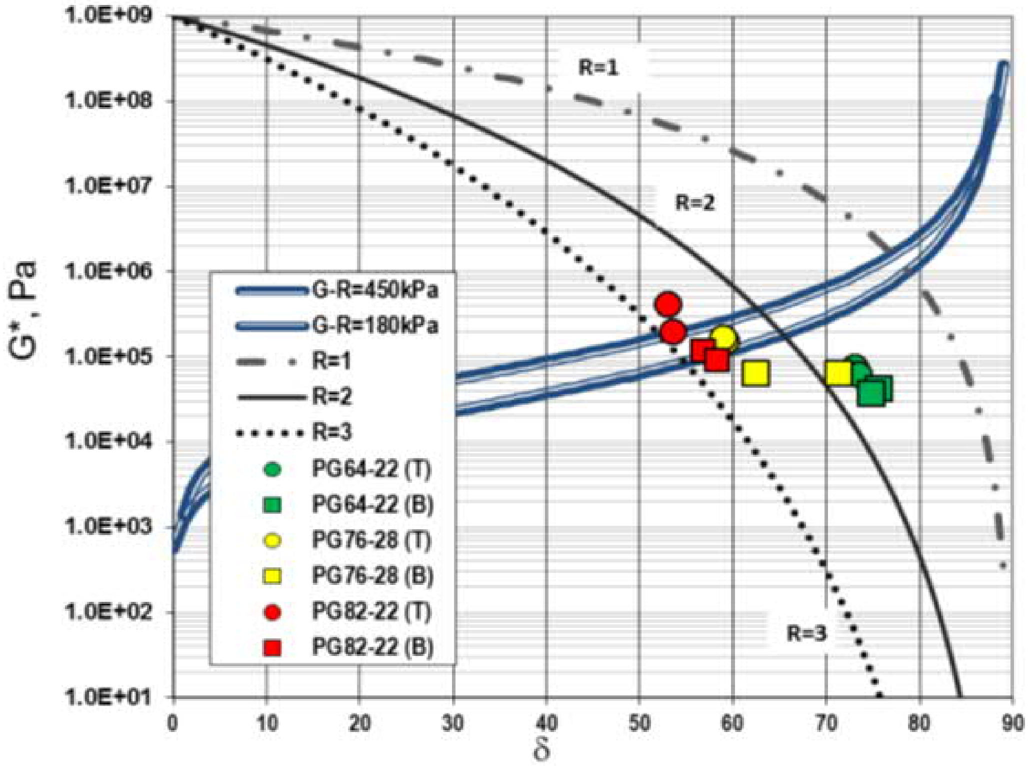

Figure 28: G-R Parameter Used in Analysing Data from Newark Airport Runway (Rowe, 2014)

It was stated earlier that the Rheological Index (R) value is an important parameter that characterises the shape of the master curve. As seen in Figure 28, an increase in the R-value is characterised by an increase in age of the binder. Further to this, an increase in the R-value results in a decrease in the crossover frequency. Analysis of the Glover-Rowe parameter has been shown to relate to environmentally induced cracking in airfield pavements.

The same parameter has been used by other researchers to assess the quality of RAP and rejuvenating agents (Rowe, 2014). The G-R and VET approaches can be interrelated with the G-R parameter plotted within VET plots and diagrams.

The concept of increased T_{VET} and reduced G^*_{VET} analysis to simulate potential for cracking can be related to R-value as detailed in the G-R model.

Rowe (2014) provided interrelationships between the G-R model and the VET model considering the G^*_{VET} and the rheological index (R) values.

$$G^*_{VET} = 10^{(9-R)}$$

Figure 29 shows the use of VET parameters and G-R models considering various binder types and damage levels.

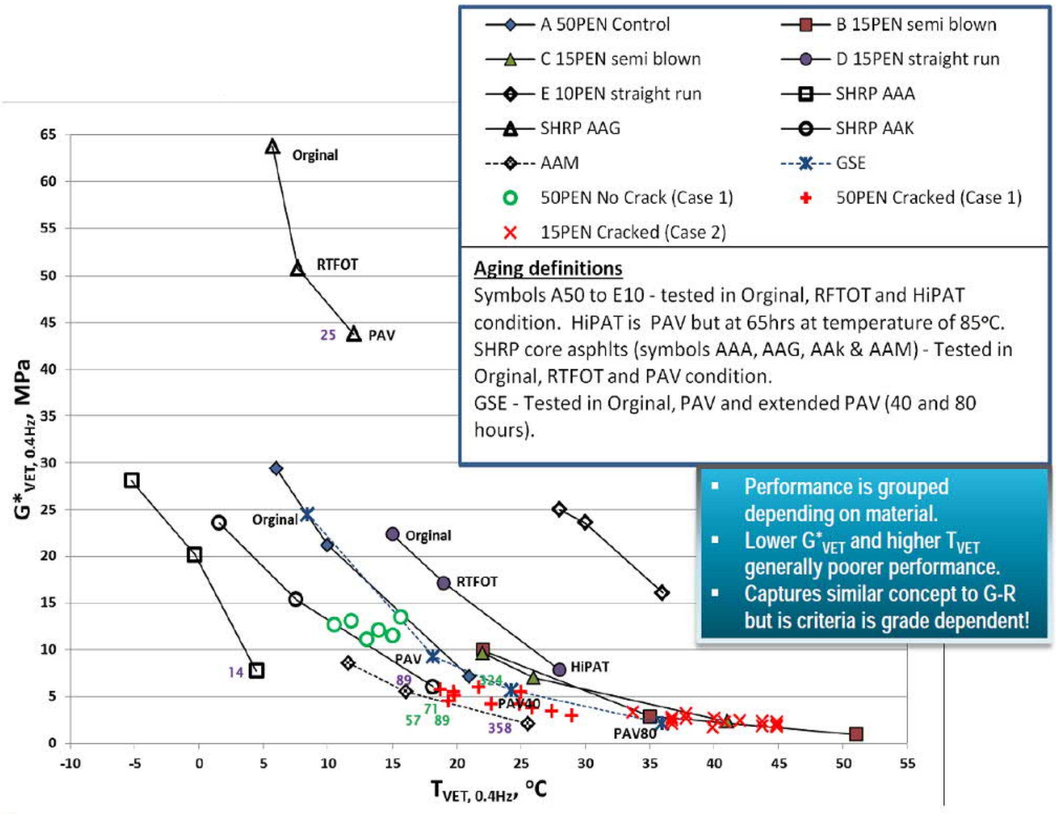

Figure 29: Interrelationships between VET Analysis and G-R Models (Rowe, 2014)

Based on the studies, it is evident that the T_{VET} and R-values are fundamentally related to the cracking potential of bitumen. In some instances, other parameters are being proposed as being related to cracking which can be clearly shown to be representations of the R-value – for example, the VET parameters.

4.6 Key Findings and Conclusions

Plots of Viscous to Elastic Transition (VET) temperatures, T_{VET}, against their respective complex stiffness modulus, G^*_{VET}, provide a useful tool for establishing how changes in the properties of bituminous materials may be associated with different levels of age hardening and distress levels (cracked or uncracked sites).

The T_{VET} is dependent on the bitumen grade, production method and age-hardening condition. Harder grade or more age-hardened bitumen lead to higher T_{VET} and lower G^*_{VET} in comparison to softer grade or less aged bitumen. Lower T_{VET} and higher G^*_{VET} indicate increased resistance to cracking and reduced ageing in the materials examined.

Migliori et al., (1999) has reported the significance of the T_{VET} to in-service performance where the T_{VET} values of recovered binders were strongly correlated with the observed surface cracking on several sites in France after several years in service.

Widyatmoko et al., (2004) presented unique relationships between binder rheology (T_{VET} and G^*_{VET}) and the presence of cracks observed on major trunk roads in the United Kingdom. The method described in this chapter is considered a useful preliminary screening tool for identifying the potential crack susceptibility of bituminous binders and may also be a useful analytical method during the forensic investigation (failure mode examination) of asphalt.

These concepts were developed further by Rowe (2014) who presented interrelationships, models and developments in rheology for different binders. Currently, other models and parameters such as the CAM and G-R models can be used to analyse and evaluate the relationship between ageing and cracking of bitumen.

Rowe (2014) provided interrelationships between the G-R model and the VET analysis considering the G^*_{VET} and the rheological index (R) values which present key trends when evaluating crack initiation and propagation in sites. An evaluation of the VET approach used in Europe demonstrates that the property G^*_{VET} is an expression of the R-value while the T_{VET} value is dependent upon the hardness of the binder.

The tool presented in this study shows the viability and potential of incorporating these models as key parameters for use as part of pavement asset management tools to evaluate and investigate pavement conditions.

5. REVIEW AND ANALYSIS OF GERMAN STONE MASTIC ASPHALT

5.1 Introduction

This chapter presents a detailed review and analysis of typical SMA used in Germany. Germany was selected to provide the detailed case study due to the durability. German SMA's are considered to have long term mechanical and performance properties.

This chapter provides a detailed review of the mix design, material properties, surface characteristics and construction techniques used in Germany. This chapter presents key findings following a site visit to Germany to investigate, evaluate and assess the design and use of SMA's. The site visit to Germany was organised by the South Bavarian Highways Authority in 2013. Sites visited include:

- Ingolstadt, Audi Sportpark.
- Landshut.
- Munich, Johann-Strauss Tunnel.
- Munich, Chiemgau Street.
- Highway A9, Direction Nuremberg, Schwabing to Allianz Arena.
- Highway A9, Beilngries.

5.2 German SMA Design Considerations

The current governing specifications for the German SMA are provided in TL Asphalt-StB 07 and ZTV Asphalt-StB 07. SMA designs in Germany are provided for 5 mm, 8 mm and 11 mm sized aggregate mixtures. There are designations for these asphalt mixtures based on loading categories.

These are detailed below:

- Special Loads designated as (‘S’)
- Normal Loads designated as (‘N’)
- Light Loads designated as (‘L’)

In heavily trafficked motorway applications “SMA 8 S” would be a typical specification. The 11 m variant is also used in other applications that might be considered comparable to the UK trunk road network (Atkins, 2015). TL Asphalt-StB 07 and ZTV Asphalt-StB 07 provides detailed specifications.

SMA was originated in Germany over 30 years ago, and a wealth of information and expertise has been acquired over that time (Nicholls et al., 2002; IAN 157/11, 2011).

The shift in methodology for the German SMA is focused on the improved design of more durable asphalt materials. A key differentiator in the German approach, compared to UK, is the use of smaller nominal sized aggregate (Atkins, 2015). To mitigate the potential reduction in early life skid resistance, grit comprised of crushed sand and lightly pre-coated chippings is applied on the surface of the German SMA immediately after installation. The application is completed while the underlying surface is still hot to facilitate improved adhesion to the surface (Atkins, 2015). The warranty period for the heaviest loaded class of roads is five years as detailed in (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). This warranty period is stipulated for new road construction projects only (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). The literature reviewed suggests that there is no warranty period for surface courses in maintenance schemes (Atkins, 2015).

Stone Mastic Asphalt (SMA) is a gap graded mixture with a coarse aggregate skeleton which is filled with mastic (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). This mastic is made of bitumen, fine aggregates (sand) and filler (Asphalt-StB 07 and ZTV Asphalt-StB 07).

To achieve a practical impermeable structure, German SMA's are specified to have a dense structure with a low in-situ air void content (≤5%). The filler-sand mixture for the German SMA is filled with the binder hence the use of a drainage inhibitor such as cellulose fibres (ZTV Asphalt-StB 07).

German SMA mixtures developed and installed in the 1970s have shown serviceable lives of 15 to 25 years (Transport Scotland, 2010). This includes German SMA's installed on heavily trafficked roads. Roads are classified in Germany based on traffic levels (RStO 01). Construction depends on the road class, which is defined before construction. The classifications are detailed below in Table 24.

Table 24: Road Classifications used in Germany (RStO 01)

Road	SV	I	II	III	IV	V	VI
B*	**>32**	**>10 to 32**	**>3 to 10**	**>0.8 to 3**	**>0.3 to 0.8**	**>0.1 to 0.3**	**<0.1**
Road Types	Motorways	Autobahn	Federal Road	Regional Road	District Road	Rural Road	Pedestrian Zone

*Dimensioning Related Action Effect: This is calculated based on weighted equivalent 10 t standard axles in the service period on which the calculation is based. This calculation is detailed in RStO 01.

The appropriate classification of the types and grades of the bituminous mixture to the building classes according to the anticipated loads is given in Table 25. As detailed in RStO 01, when selecting the layer thickness and arrangement, the guidelines on the standardisation of the top layer of traffic areas are definitive. In cases where alternative layer thicknesses are required, the values detailed in Table 25 to Table 28 are important as it relates to material type, options and construction requirements.

Table 25 to Table 28 shows that the specification for asphalt surfaces consists of an asphalt basecourse of either asphalt concrete, mastic asphalt with chippings, mastic asphalt or porous asphalt depending on the type of road surface and category.

The guidelines on the standardisation of the top layer (surface course) of traffic areas are classified according to special and normal loads. The types and grades of bituminous mixture for special loads are always encountered in building classes SV and I to III, normal loads are detailed in building classes IV and V while light loads are detailed in building class VI, on cycle paths and footpaths. These loads may be increased as a result of climatic influences such as:

- High temperatures over extended periods.
- Intensive direct sunlight, e.g. on south exposed slopes.

Grades of bituminous mixture which are designed for special loads are marked with the letter “S” at the end of their designations as presented in Table 25.

The grades of bituminous mixture which are designed for normal loads are marked with the letter “N” and grades of bituminous mixture which are designed for light loads are marked with the letter “L” at the end of their designations (Table 25).

Table 25: Classification of Bituminous Mixtures (TL Asphalt-StB 07 and ZTV Asphalt-StB 07)

<table>
<tr><th rowspan="2">Type of Surface</th><th rowspan="2">Asphalt Road Base</th><th rowspan="2">Asphalt Binder Course</th><th rowspan="2">Asphalt Wearing Course</th><th colspan="4">Base Course of</th></tr>
<tr><th>Asphaltic Concrete</th><th>Mastic with Chippings</th><th>Mastic Asphalt</th><th>Porous Asphalt</th></tr>
<tr><td>SV and I</td><td rowspan="3">AC 32 T S
AC 22 T S</td><td rowspan="2">AC 22 B S
AC 16 B S</td><td rowspan="5">-</td><td>-</td><td rowspan="3">SMA 11 S
SMA 8 S</td><td rowspan="3">MA 11 S
MA 8 S
MA 5 S</td><td rowspan="3">PA 11
PA 8</td></tr>
<tr><td>II</td><td rowspan="2">AC 11 D S</td></tr>
<tr><td>III</td><td>AC 16 B S</td></tr>
<tr><td>IV</td><td rowspan="3">AC 32 T N
AC 22 T N</td><td>(AC 16 B N)</td><td rowspan="2">AC 11 D N
AC 8 D N</td><td rowspan="2">(SMA 8 N)</td><td rowspan="3">(MA 11 N)
(MA 8 N)
(MA 5 N)</td><td rowspan="4">-</td></tr>
<tr><td>V</td><td rowspan="3">-</td></tr>
<tr><td>VI</td><td rowspan="2">AC 16 T D</td><td rowspan="2">AC 8 D L
AC 5 D L</td><td>(SMA 8 N)
(SMA 5 N)</td></tr>
<tr><td>Cycle Paths and Footpaths</td><td>AC 32 T N
AC 22 T L</td><td>-</td><td>(MA 5 N)</td></tr>
</table>

The appropriate binder types and grades according to the anticipated loads are given in Table 26.

Table 26: Binder Types and Grades (ZTV Asphalt-StB 07)

<table>
<tr><th rowspan="2">Type of Surface</th><th rowspan="2">Asphalt Road Base</th><th rowspan="2">Asphalt Binder Course</th><th rowspan="2">Asphalt Wearing Course</th><th colspan="4">Base Course of</th></tr>
<tr><th>Asphaltic Concrete</th><th>Mastic Asphalt with Chipping</th><th>Mastic Asphalt</th><th>Porous Asphalt</th></tr>
<tr><td>SV and I</td><td rowspan="3">50/70
(30/45)</td><td rowspan="3">PMB 45
30/45
(PMB 25)</td><td rowspan="5">-</td><td>-</td><td rowspan="2">PMB 45</td><td>20/30
(PMB 25)</td><td rowspan="3">PMB
40/100-65 H</td></tr>
<tr><td>II</td><td>PMB 45</td><td rowspan="2">20/30
(PMB 45)</td></tr>
<tr><td>III</td><td>PMB 45
50/70</td><td>PMB 45
(50/70)</td></tr>
<tr><td>IV</td><td>70/100
(50/70)</td><td>50/70</td><td>50/70</td><td>50/70</td><td rowspan="4">30/45</td><td rowspan="4">-</td></tr>
<tr><td>V</td><td rowspan="3">70/100</td><td rowspan="3">-</td><td rowspan="2">50/70
70/100</td><td rowspan="2">70/100</td></tr>
<tr><td>VI</td><td rowspan="2">70/100</td></tr>
<tr><td>Cycle and Footpaths</td><td>70/100</td><td>-</td></tr>
</table>

It must be noted that roundabouts are designed based on the “next” higher building class for the roundabout which experiences the greatest loads. Asphalt road bases are designed based on the envisaged method of placement either single or multiple layers. Asphalt road bases with envisaged placement thicknesses > 16 cm, placement involving multiple courses or layers is also feasible. Polymer Modified Binder (PMB) is preferable, especially for roads and traffic areas subjected to high loads and special loads (Asphalt-StB 07 and ZTV Asphalt-StB 07).

5.2.1 Construction Requirements

There is a requirement for taking cores after laying asphalts in Germany. The cores are taken so that an in-situ air void is measured, and it is in accordance with the specification (Table 27). The general trends that can be deduced from Table 27 includes a requirement for materials with reduced air void contents in comparison to requirements on Highways England Strategic Road Network.

Table 27: In-Situ Air Voids Requirements (TL Asphalt-StB 07 and ZTV Asphalt-StB 07)

Stone Mastic Asphalt	Unit	SMA 11S	SMA 8 S	SMA 5 S	SMA 8 N	SMA 5 N
Min Void Content	(%)	V_{min} 2.5	V_{min} 2.5	V_{min} 2.0	V_{min}1.5	V_{min}1.5
Maximum Void Content	(%)	V_{max}3.0	V_{max} 3.0	V_{max}3.0	V_{max}3.0	V_{max}3.0
Voids Filled with Bitumen	%	To be Specified	To be Specified	To be Specified	To be Specified	To be Specified
Proportional Rut Depth	%	To be Specified	To be Specified			

Table 28 presents the design compaction and air void requirements for typical installed SMA in Germany.

Table 28: Design Air Voids Requirements (TL Asphalt-StB 07 and ZTV Asphalt-StB 07)

Characteristics of Layer	Unit	SMA 11 S	SMA 8 S	SMA 5 S	SMA 8 N	SMA 5 N
Paving Thickness	cm	3.5-4.0	3.0-4.0	2.0-3.0	2.0-3.5	2.0-3.0
Paving Amount	kg/m^2	85-100	75-100	30-50	50-85	50-75
Degree of Compaction	%	>97	>96	>96	>97	
Void Content	Vol.-%	<5		-	<5	
Gritting Material	kg/m^2	0.5-1.0 kg/m^2 aggregates 1/3 mm				

The German standard stipulates that surfaces are gritted with dedusted crushed sand and lightly pre-coated chippings (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). This is to increase the initial skid resistance for the installed German SMA (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). The German SMA standards do not specify texture depth requirements for the surface course systems.

Typical dedusted crushed sand and/or lightly pre-coated chippings are summarised below:

A. Fraction 1/3 mm: 0.5 – 1.0 kg/m^2
B. Fraction 2/5 mm: 1.0 – 2.0 kg/m^2

During compaction gritting material is applied on the hot surface for better adhesion (Figure 30).

Figure 30: Gritting Operations for German SMA

It is important to note that the German requirement for tread depth is the same as in the UK at 1.6 mm for ordinary cars. Therefore, the tread depth is not a factor in maintaining lower texture depth on the surface of roads in Germany. Skid resistance is measured based on German SKM method (SCRIM system). It is measured four weeks after the surface is laid and annually thereafter.

Measuring Speed/Time of Acceptance:

- 80 km/h μSKM = 0.46
- 60 km/h μSKM = 0.51
- 40 km/h μSKM = 0.56

Measuring Speed/End of Warranty:

- 80 km/h μSKM = 0.40
- 60 km/h μSKM = 0.45
- 40 km/h μSKM = 0.49

Tolerance for Single Value Measurement: 0.03 μSKM

The warranty period for new projects is:

- Five years for road classes SV and I
- Four years for road classes II-VI

The warranty period for the maintenance schemes for the binder/surface course is stated in Table 29.

Table 29: Warranty Requirements

Years/Layer	Layer Thickness	Quantity of Material	Surface Course	Binder Course
2 Years	≥ 2 cm	≥ 50 kg/m^2	X	-
3 Years	≤ 8.5 cm	≤ 215 kg/m^2	X	X
4 Years	> 8.5-11.5 cm	> 215-290 kg/m^2	X	X
5 Years	> 11.5 cm	> 290 kg/m^2	-	X

5.2.2 Key Factors for Consideration

The most important difference between the German and English approach is in the design of SMA. In England, SMA must be designed to provide the macro/micro texture depth requirements for the safety of the road users. The German design is based on the low void and higher binder content (mostly polymer-modified with fibres) to increase the durability of the produced asphalt. Nicholls et al., (2009) states that: “the success of the German approach was demonstrated in the visual monitoring of sites on local Autobahns. These sites did not show any particular concerns about the lack of skid resistance for the road users.”

Further to these factors stated above, it appears that the German traffic management requirements are less restrictive than the English equivalent. There are many surfacing schemes in Germany where surfacing has been laid with one paver in full width while the whole carriageway is closed to traffic (Figure 31). ZTV Asphalt-StB 07 (Section 2.1) stipulates that:

- "it should be determined when preparing the specifications whether the asphalt layers can be placed along the entire width of the roadway without joints or determined if using the "hot to hot" technique" is a viable option.
- It should furthermore be determined whether a continuous mix supply (by using a feeder) can be utilised.

If applicable, these should be added to the contract specification documents. The use of wide pavers, multiple roller compactors under full closures eliminates joints on the road. This is a key factor capable of improving durability as there will be no longitudinal joints between the lanes and therefore less chance of deterioration. The main difference between the German warranty and English warranty requirements is that in England the warranty period is five years for either maintenance or new schemes regardless of the road category. In England, there are no in-situ air void requirements.

Figure 31: The Use of Wide Pavers, Multiple Roller Compactors under Full Closures

A key factor for consideration is the widespread use of PMB's on the German network in comparison to the UK. The traffic load on German federal roads has strongly increased during the last few decades. This is one of the reasons why the use of PMB has increased instead of using "paving grade bitumen" In 2002, the proportion of PMB used in road construction was 13.9%. By 2008, it was already 18.2%. The increased use of PMB has been due to the following factors:

- Increased plasticity range.
- Increased low temperature.
- Improved fatigue behaviour.
- Better adhesion.

The use of the specified PMB in Germany reduces the risk of crack formation during the cold season and increases heat resistance in summer (TL Asphalt-StB 07 and ZTV Asphalt-StB 07). The use of PMB's improves the service life of the roads preventing ingress of moisture to underlying layers in the pavement. The German SMA mixtures have proven track records that show improved durability, excellent riding characteristics and low noise characteristics (Nicholls et al., 2009).

5.3 German Site Visit

This section of the study presents key findings following a site visit to Germany to investigate, evaluate and assess the design and use of SMA's. The site visit to Germany was organised by the South Bavarian Highways Authority in March 2013.

The sites visited in Germany show the advantage of low air voids contents in the durability of SMA mixtures (Figure 32 and Figure 33). However, it is noted that the relatively high texture depths specified in MCHW Clause 900 on high-speed trunk roads in the UK preclude the use of mixtures with the sort of low air voids contents specified for German Autobahns.

Figure 32: Site Visit Highway A9, Beilngries, SMA 8 S

Figure 33: Ingolstadt / Audi Sportpark, SMA 11 S + SMA Binder 16

Figure 34: Landshut – SMA 5 Material

Figure 35: Intersection at Landshut Junction – SMA 5 Material

It was noted that the SMA 5 material used in Landshut as depicted in Figure 34 and Figure 35 is heavily trafficked by Heavy Goods Vehicle (HGVs) daily. This resulted in the Bavarian Authority specifying a dense SMA 5 for this site to provide a durable asphalt material capable of withstanding high stresses because of traffic and complex geometric designs required for this site location (TL Asphalt-StB 07 and ZTV Asphalt-StB 07).

This practice is in line and synonymous with the recently published IAN 157/11 in England where the recommendation is to use a denser Thin Surface Course System (10 mm size aggregates) in high-stress locations. However, it must be noted that due to the texture depth requirement in England, the use of smaller size aggregates (< 10 mm) has been limited.

5.3.1 Assessment of German SMA Samples

Following the site visit, three samples were obtained from a site which was constructed in 2007 (aged 9 years at the time of extraction and subsequent analyses).

The three cores obtained were produced using three different aggregate rock types that included Rhyolite, Diabase and Greywacke. The SMA was produced in accordance with (ZTV Asphalt – StB 2001).

The composition, typical mix design, material properties and layer thickness are presented in Table 30.

Table 30: Composition and Material Properties of the German SMA Samples

Properties	Units	Sample Number 1.5 (Rhyolite)	Sample Number 2.5 (Diabase)	Sample Number 3.5 (Greywacke)
Mixture				
Sieve Size > 2 mm	M.-%	75.1	74.1	74.2
Sieve Size 0.063 mm – 2 mm	M.-%	14.5	13.9	15.0
Filler	M.-%	10.4	12.0	10.8
Coarse Aggregate Content	M.-%	51.6	48.1	47.0
Binder Content	M.-%	6.7	6.5	6.7
Softening Point	°C	66.0	65.2	68.2
Penetration	1/10mm	33	33	32
Elastic Recovery/Provision	%	74	72	73
Mix Density	g/cm3	2.376	2.521	2.489
Bulk Density of the Marshall Specimens	g/cm3	2.318	2.473	2.437
Air Voids on the Marshall Specimens	Vol.-%	2.4	1.9	2.1

Compacted Layer				
Bulk Density of the Core	g/cm3	2.348	2.511	2.458
Air Void Content of the Core	Vol.-%	1.2	0.4	1.2
Layer Thickness	cm	4.7	4.7	4.7
Binder: 25/55-55				

As detailed in Table 30, it was observed that the SMA mixtures were produced using a high proportion of coarse aggregates. The German SMA samples were designed to have relatively low initial air voids, specifically: between 2% and 4% (laboratory mix design) and not greater than 6% (in situ). After 9 years in service, the residual air voids ranged between 0.4% and 1.2%.

The recovered binder content of the German SMA samples ranged from 6.5% to 6.7% for all three samples produced in accordance with (ZTV Asphalt – StB 2001). This indicates good and consistent specification with adequate production control between projects. The texture depth, Pendulum Test Value (PTV) and stiffness test (ITSM) result on the three core samples in accordance with BS EN 13036-1, BS EN 13036-4 and BS EN 12697-26 respectively are shown in Table 31.The texture depth results as detailed in Table 31 indicate that the values exceeded 0.8 mm after nine years of trafficking. The variations in texture depth values, between 0.8 mm and 1.1 mm suggests good consistency of the surface characteristics of these three different surface course materials. These results suggest that it is possible to achieve texture depth values not less than 0.8 mm even at air voids of 0.4% – 1.2% in situ, as shown in Table 30 and Table 31. The pendulum test values as detailed in Table 31 show that after trafficking for nine years, the values were consistently above 70 indicating good retention on wet skid resistance characteristics. Stiffness values may not be a primary requirement for TSCS, but it can provide an indication of the state of ageing of the material and the associated risk to durability.

The stiffness values ranged between 4000 – 5000 MPa as detailed in Table 31. These values are comparable to similar asphalt surfacing materials with a good surface condition after a few years in service. This may suggest that the German SMA samples have reasonably good resistance to age hardening.

Table 31: Mean Texture Depth, Pendulum Test Value and Stiffness Test Results

Sample Reference	Bulk Density (kg/m^3)	Texture Depth (mm)	Pendulum Test Value (PTV)	ITSM at 20°C (MPa)
1.5	2345	1.1	82	3930
2.5	2506	1.0	71	3660
3.5	2462	0.8	70	4740

5.3.2 Rheological Properties of German SMA Samples

The rheological properties of recovered binder from the German SMA samples were obtained using principles as detailed in BS EN 14770. The complex modulus (G*), calculated penetration and softening point using the DSR are presented in Table 32. Considering the PMB used in producing the samples (PMB 25/55-55 as detailed in Table 30), the recovered binder shows that the rheological properties of the bitumen are still performing optimally with minimal ageing after nine years in service.

Table 32: Complex Modulus, Penetration and Softening Point Test Results

Sample Reference	G* (Pa) at 0.4Hz & 25°C	Penetration Indices (PI)	Penetration (dmm) at 25°C	Softening Point (°C)
1.5	7.29E+05	1.4	34	65.4
2.5	6.91E+05	1.6	36	66.0
3.5	4.58E+05	1.1	45	60.2

The black diagram depicting plots of the phase angle vs the complex modulus is shown below in Figure 36. The black diagram allows all the dynamic data to be presented in one plot (Airey, 2002). For comparison, a good performing PMB was used; specifically, after Rolling Thin Film Oven Test (RTFOT) (SBS 80/60 R) and after High Pressure Ageing Test (HiPAT) (SBS 80/60 H).

A standard 40/60 pen after HiPAT (40/60 Pen H) is included in the analysis. The RTFOT was used to simulate the ageing which occurs during the mixing, transportation and laying processes, while the HiPAT was used to simulate the ageing which occurs in a binder while service.

Figure 36 displays the black diagram for the samples.

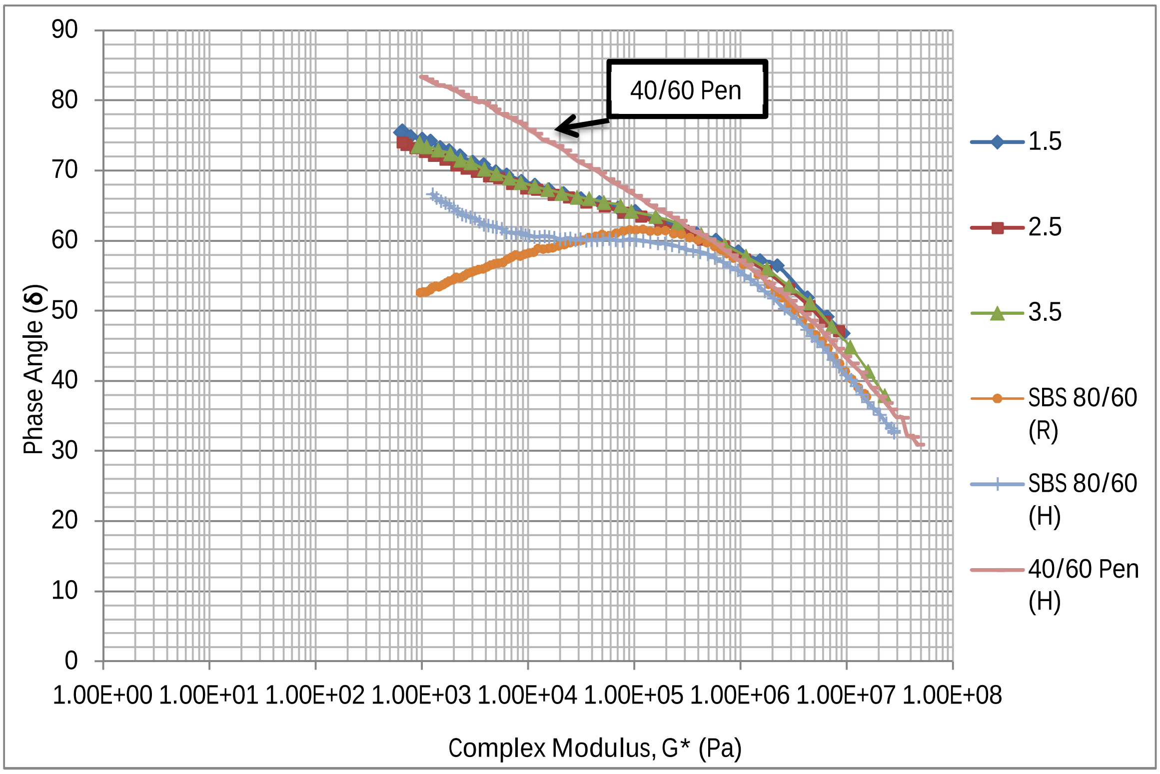

Figure 36: Black Diagram – German SMA Samples

The German SMA samples (1.5 - Rhyolite, 2.5 – Diabase and 3.5 – Greywacke) showed comparable results in the black diagram, consistent with the results presented in Table 32. At lower phase angles, all materials displayed had consistent and comparable dynamic rheological characteristics. However, as seen in Figure 36, a more pronounced difference was observed at higher phase angles with the 40/60 Pen (H) after HIPAT showing the highest phase angle (more viscous response) at G* values near the softening point of the binder. This was followed by the three German binders and then the reference SBS 80/60 binders.

As expected, the 40/60 Pen (H) showed the highest stiffness (G*) which indicated greater susceptibility to age-hardening in comparison to the PMB's; these trends are illustrated in Figure 37.

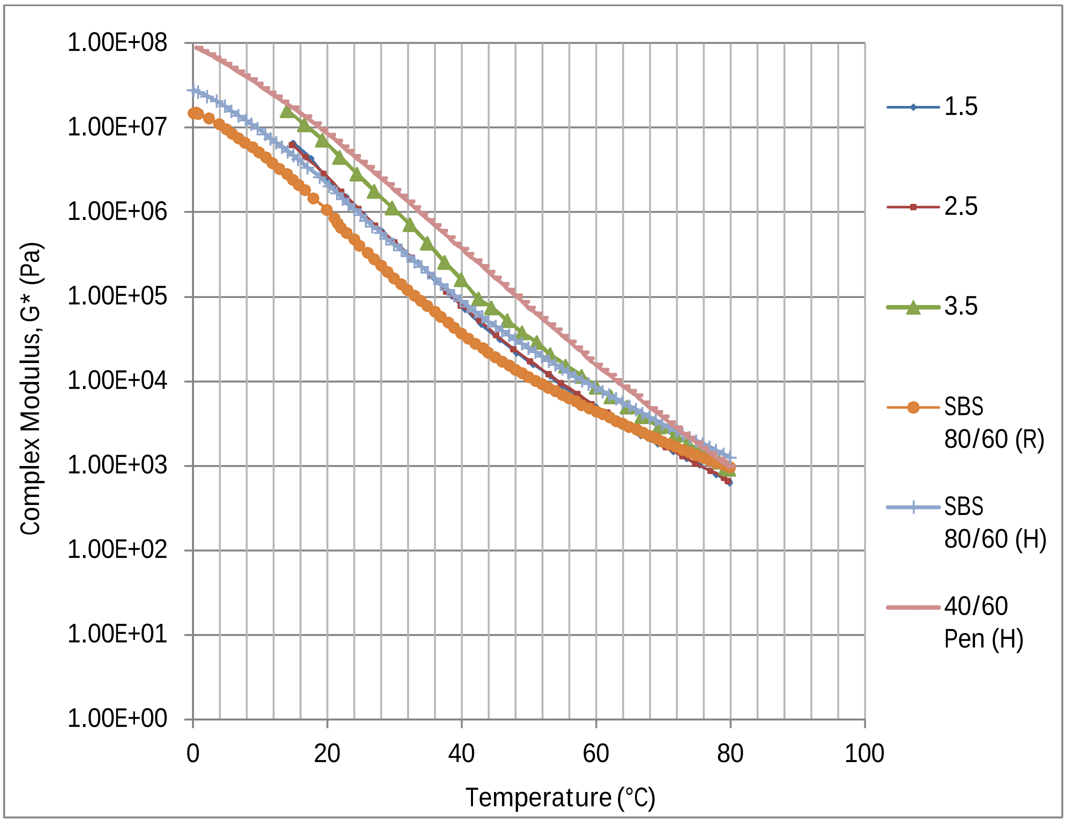

Figure 37: G* vs Temperature for German SMA Samples

In this chart (Figure 37), the SBS 80/60 H showed some similarities with the German SMA binders on the temperature susceptibility of G* values.

Figure 38 showed that the German SMA binders had a consistent viscoelastic response over the service temperature range (0°C to 80°C).

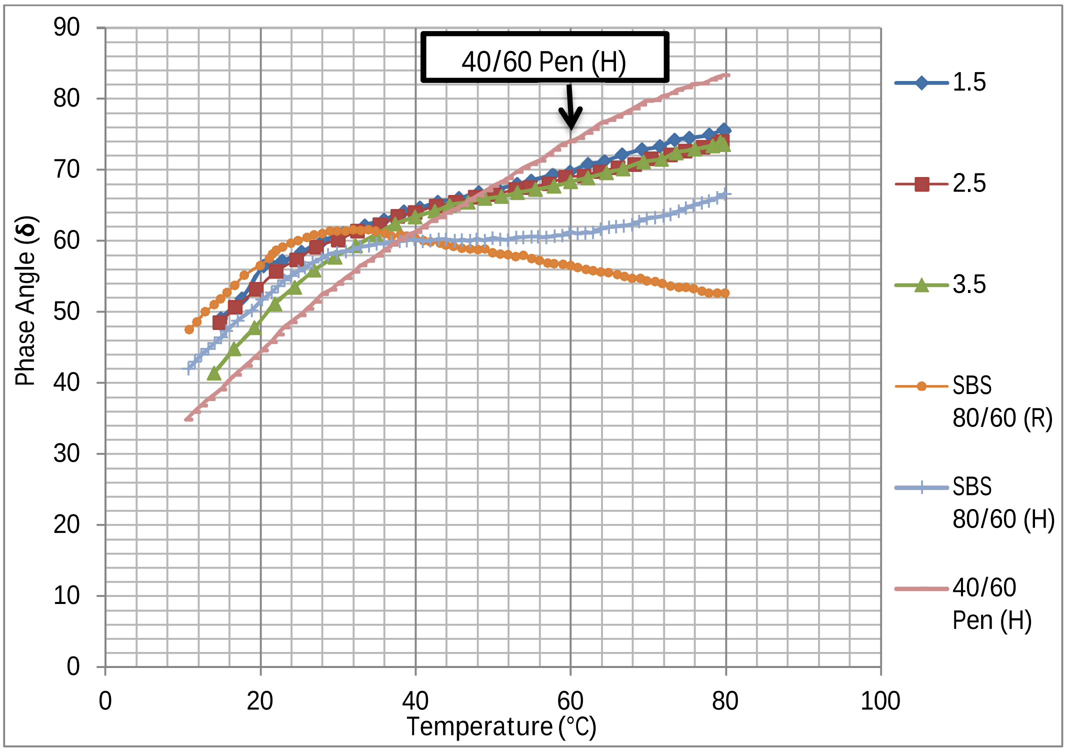

Figure 38: Phase Angle (δ) vs Temperature

The 40/60 Pen (H) as seen in Figure 38 was most prone to cracking and deformation at low and high temperatures respectively. From low to intermediate temperatures (up to 30ºC), the German SMA binders seem to have similar viscoelastic properties as the reference PMB (SBS 80/60); at higher temperatures the German binders show a more viscous response suggesting lower resistance to deformation.

5.4 Summary

After nine years in service, the polymer modified thin SMA samples were extracted from motorways in Germany, the recovered binder content, ranged between 6.5 and 6.7%; this may indicate good and consistent specification and production control between projects. Stiffness values seem to be comparable to similar asphalt surfacing materials with a good surface condition after a few years in service. This may suggest the German SMA samples have reasonably good resistance to age hardening.

While there was no information available on the rutting performance of this material, it was suspected that densification might have had taken place as shown by the residual air voids between 0.4% and 1.2%. Nevertheless, the SMA samples maintained good surface macrotexture for nine years (the mean texture depth was found to be greater than 0.8 mm). Furthermore, the pendulum test value after trafficking for nine years was consistently above 70 indicating good retention on wet skid resistance characteristics.

6. REVIEW AND ANALYSIS OF HIGHWAYS ENGLAND NETWORK CONDITION DATA FOR THIN SURFACE COURSE SYSTEMS

6.1 Introduction to Highways England Value Management Procedures

Highways England Value Management (VM) provides a technical review of proposed treatment options and generates a VM score for the preferred improvement opportunity or renewal project. The generated VM score provides the basis for the prioritisation and funding of projects for roads in England.

Highways England's VM guideline stipulates that the VM process should provide the following main benefits:

- Review, confirm and consolidate the project objectives.
- Choose between alternative project options and benefits.
- Provide a technical review of the project submissions.
- Contribute to the achievement of Highways England's strategic objectives
- Provide VM scores for projects that can be used by Network Delivery and Development (NDD) Central and Service Managers to help develop a Forward Programme for HE.
- As good governance, keeping records of the changes to each project in terms of impacts and benefits achieved at every stage of the project development is important.

The key outcome required from HE VM procedures includes the fact that: identified network needs are addressed and prioritised, projects are promoted in a way that address the greatest needs of the network. The VM process maximises value for money in addition to prolonging the life of the asset as required.

A key component of the VM process is the use of Simple Surfacing Schemes for assessment of roads in applicable situations. Simple Surfacing Schemes are primarily focussed on lengths of carriageway where there are no structural problems. Deteriorations are limited to the surface course layer. Simple Surfacing Schemes require renewal of only the surface course. This necessitates the need for a simplified development and assessment treatment process.

Simple Surfacing Schemes are comprised of Highways England Pavement Management Systems (HAPMS) Sections of carriageway where:

- The surface course is at increased risk of rapid failure due to its age; and/or
- The surface course is exhibiting surface only defects (such as fretting).

The age at which surface courses are at an increased risk of rapid failure (Trigger Age) are given in Table 33.

Table 33: Trigger Age for Risk-Based Intervention (Atkins, 2017)

Surface Course Material	Years
Hot Rolled Asphalt (HRA)	20 years
Thin Surface Course System (TSCS)	10 years

To identify lengths of the carriageway which contain only surface defects, it is important to separate sections of roads with no structural deterioration. This is achieved by reviewing the HAPMS. The outline approach used to identify whether an individual HAPMS Section is free of structural defects is detailed below:

1. 100 m Traffic Speed Structural Surveys (TRASS) or historical Deflectograph data must indicate that no structural problems are present within the HAPMS chainage section.
2. 10 m rutting data from TRASS show that all rutting present in the lanes surveyed within the Section is less than 11 mm.
3. The Section must not contain surface courses with visual evidence of structural defects.
4. The detailed approach to be used for identifying HAPMS Sections that are suitable for inclusion within a Simple Surfacing Scheme is set out in Figure 39 and its accompanying notes.
5. All lanes within the HAPMS Section should be considered at each point in the flowchart.
6. TSCS which are less than five years old but contain defects should be investigated for potential repair under specified performance guarantee.

Figure 39 presents a flow chart for identifying simple surfacing schemes (Atkins, 2017).

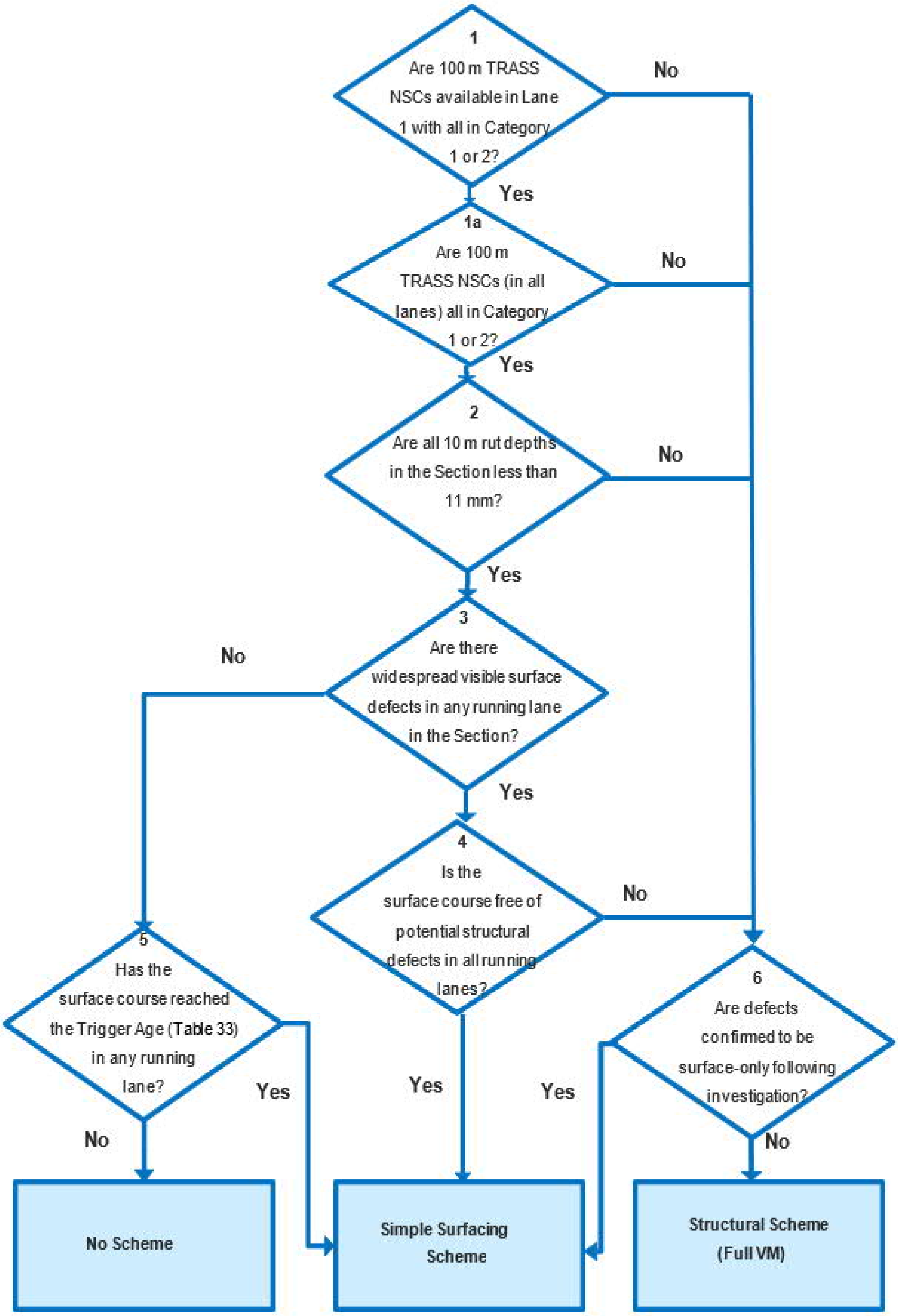

Figure 39: Flow Chart for Identifying Simple Surfacing Schemes (Atkins, 2017)

In addition to Simple Surfacing Schemes, HD 30/08 presents a detailed investigation and assessment procedure as detailed below in Figure 40.

Stage 1. Review Network Survey Surface Condition Data and Identifying Possible Maintenance Schemes

TRACS or SCANNER, SCRIM, safety, routine or other visual inspections and Deflect TRACS or SCANNER, SCRIM, safety, routine or other visual inspections and Deflectograph (for some networks).

↓

Stage 2. Collate and Review Existing Data

TRASS, traffic, construction and maintenance history data

↓

Stage 3. Plan Scheme-Level Surveys and Investigations

↓

Stage 4. Carry out Scheme-Level Surveys

- Pavements - Visual Condition Survey, Cores etc.
- Other (as required): Earthworks, drainage etc.

↓

Stage 5. Interpretation of Data

↓

Stage 6. Design Treatment

Figure 40: Maintenance Assessment Procedure (Adopted from HD 30/08)

6.2 Highways England Network Condition for TSCS

This section presents a factual report of HE network condition for TSCS obtained from the HAPMS database. The analysis focused on findings from 30 sites selected from the North East, East, South East and South West of England as depicted in Figure 41. The regions selected comprised of Areas 1, 4, 6, 8, 14 of HE SRN.

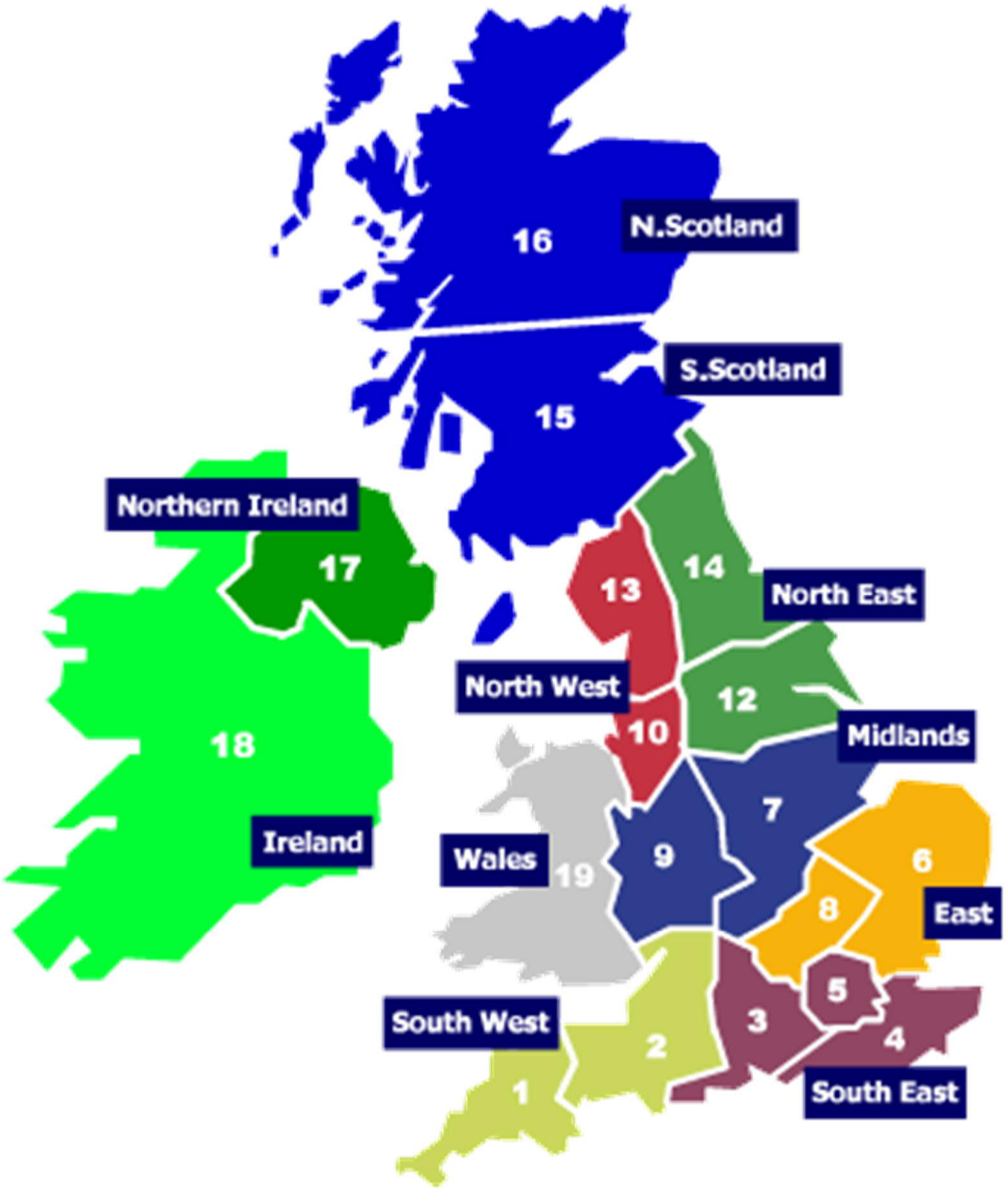

Figure 41: Highways England Network Management Map

The following parameters were obtained for each site.

Age (years):

The "Date Laid" data from HAPMS is used to calculate the Age (in years) from 01/04/13.

Age Range:

The following age-based classification was adopted for this study:

- < 5 years
- 5 to 10 years
- > 10 years

The lower limit of 5 years was selected considering this is the "surfacing integrity - performance guarantee period" required by MCHW Clause 942 (Highways England, 2018a).

Material Name:

HAPMS Construction Records (current as at 01/04/13) provided this information. The "Material Name" options were "Thin Surfacing (Generic)", "Thin Surfacing (Polymer)" and "Thin Surfacing (Fibre)".

Texture Depth:

TRACS record texture data was downloaded from HAPMS for all sites investigated for the project. The data sets were current as at 1st April 2014 - this being the approximate date that the analyses commenced. For each core location, the 10 m texture data was recorded.

Season Laid:

Information on the season the TSCS was laid was obtained. Guidance from IAN 157/11 defined the laying season for TSCS as “April to October - Not Winter” and “November to March as Winter".

<u>Visual Condition Surveys:</u>

Visual Condition Survey data was used to identify the presence of fretting defects recorded at individual sites evaluated for this project. The classifications used to ascertain the severity of fretting is detailed below:

- No Fretting
- Minor Fretting
- Major Fretting

In addition to reviewing HAPMS data for TSCS, a total of 122 cores were obtained from selected sites. Visual Condition Inspection was carried out and categorised based on the level of fretting.

Typical tests carried out on these samples include:

- Compositional Analysis in accordance with BS EN 12697-1 (2012) and 2 (2015).
- Mixture volumetric in accordance with BS EN 12697-5 (2009), BS EN 12697-6 Procedure B (2012) and BS EN 12697-8 (2018), respectively.
- Indirect Tensile Stiffness Modulus (IT-CY) in accordance with BS EN 12697-26 (2018).
- Bitumen Rheology in accordance with BS EN 12697-3 (2005) and BS EN 14770 (2012).

6.2.1 Compositional Analysis and Volumetric Test Data

Compositional analysis was carried out to obtain the binder content and particle size distribution in accordance with BS EN 12697-1:2012 and BS EN 12697-1:2015 respectively.

6.2.2 Mixture Volumetric

The volumetric properties of all specimens were evaluated for this study. This evaluation includes measuring the maximum density, bulk density and the air void content of specimens. The tests were carried out in accordance with BS EN 12697-5: 2009, BS EN 12697-6: 2012 and BS EN 12697-8: 2018

6.2.3 Indirect Tensile Stiffness Modulus (IT-CY)

The Indirect Tensile Stiffness Modulus (IT-CY) test was conducted on samples to measure the indirect tensile modulus of elasticity. The IT-CY test is conducted for the measurement of small strains on bituminous mixtures by applying impulse loading on a vertical diameter of a cylindrical specimen. The stiffness modulus was determined at a temperature of 20°C using the procedure described in BS EN 12697-26: 2018.

The IT-CY test is non-destructive and measures the viscoelastic response of a material. The test makes use of cylindrical specimens either cored from the field or prepared in the laboratory with a diameter of 100 mm or 150 mm.

The thickness of samples suitable for testing range from 30 mm to 80 mm. Table 34 provides a summary of the test parameters for the IT-CY. The test configuration for the IT-CY test is shown below in Figure 42.

Table 34: IT-CY Test Parameters

Parameter	Protocol
Specimen Thickness	30 – 75 mm
Rise Time	124±4 ms
Target Horizontal Deformation	5±2 µm (100 mm diameter) 7±2 µm (150 mm diameter)
Pulse Duration	3 seconds
Wave Form	Haversine
Number of Conditioning Pulses	5 pulses
Test Temperature	20±5 µm (100 mm diameter)
Poisson's Ratio	0.35

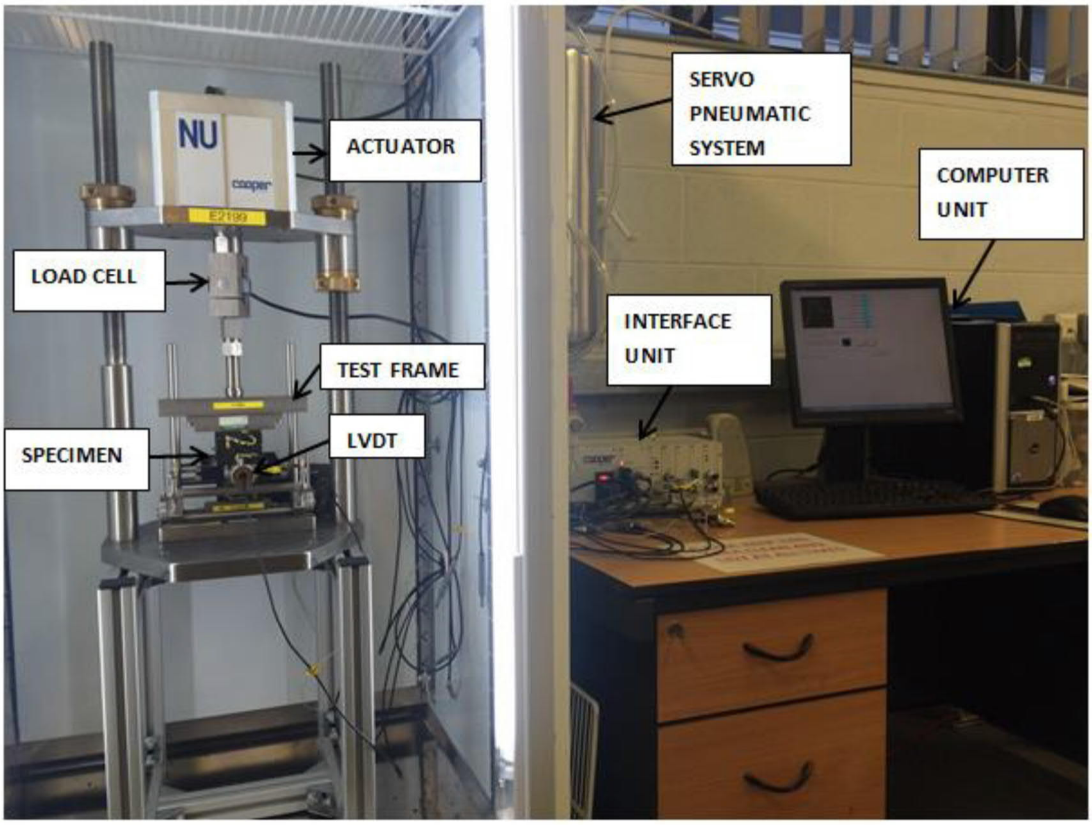

Figure 42: IT-CY Test Configuration

6.2.4 Bitumen Rheology

The binder content by percentage mass of the total asphalt mixture was determined through complete extraction of the binder in line with specifications as detailed in BS 598: Part 102. The rheological properties of the binders were studied by investigating their rheological behaviour by performing the Frequency-Temperature Sweep test using a Dynamic Shear Rheometer (DSR) over a range of different temperatures (5°C to 80°C) and frequencies (0.1Hz to 10Hz). The test was performed in accordance with BS EN 14770:2012.

The results from the bitumen rheology provide key information on the mechanical and performance properties of the binder at different temperatures and loading frequencies. Information obtained from the bitumen rheology provides the basis for conducting Viscous to Elastic Transition (VET) temperature analysis as detailed in Section 4.5.

6.3 Review of Highways England Network Condition Data for TSCS

This section of the report provides results and findings following a detailed review and analysis of the HAPMS database, visual condition survey of HE SRN and laboratory investigation of typical TSCS cores obtained from site. The information evaluated and analysed provides key information and trends of Highways England Network Condition Data for TSCS.

Please note that charts in this project graphically display the variability in the data using error bars. These error bars show the standard deviation. The standard deviation gives an indication of how closely clustered the data points are around the mean values calculated.

The age profile of TSCS on the SRN obtained from HAPMS is summarised below in Figure 43. This shows that most roads are less than ten years old.

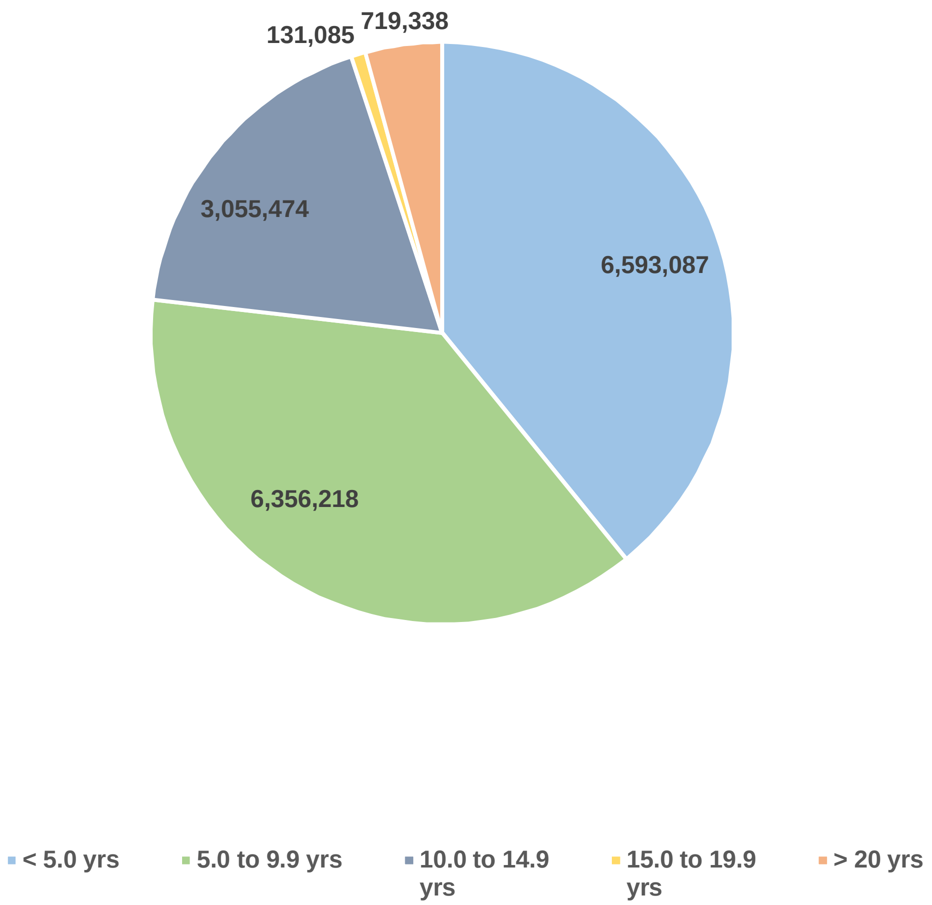

Figure 43: The Age Profile of Roads on the Strategic Road Network

Figure 44 provides a detailed breakdown of the age profile of TSCS on the SRN by length based on the network areas. The HAPMS investigations showed that 39% of the total length of TSCS on the HE network is less than five years old. Approximately, 77% of the entire length of TSCS on the HE network is less than ten years old.

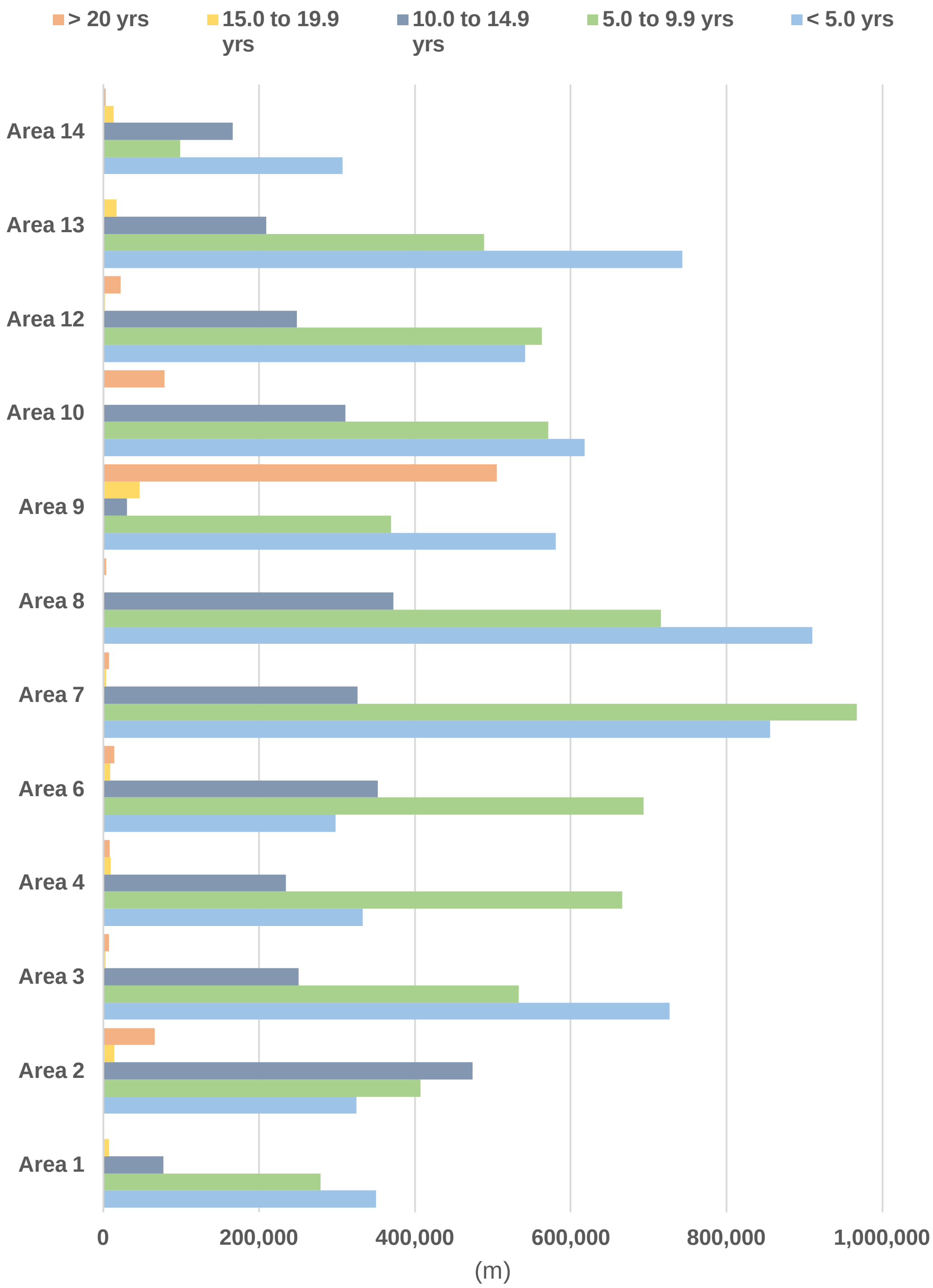

Figure 44: TSCS Age Profile by Length and Network Area

The proportion and type of TSCS used on the SRN are detailed below in Figure 45. The analysis is restricted to permanent lanes and hard shoulders only. Area 1 has the most significant proportion of TSCS incorporating fibres. Area 13 has the largest percentage of TSCS with polymer modified binders.

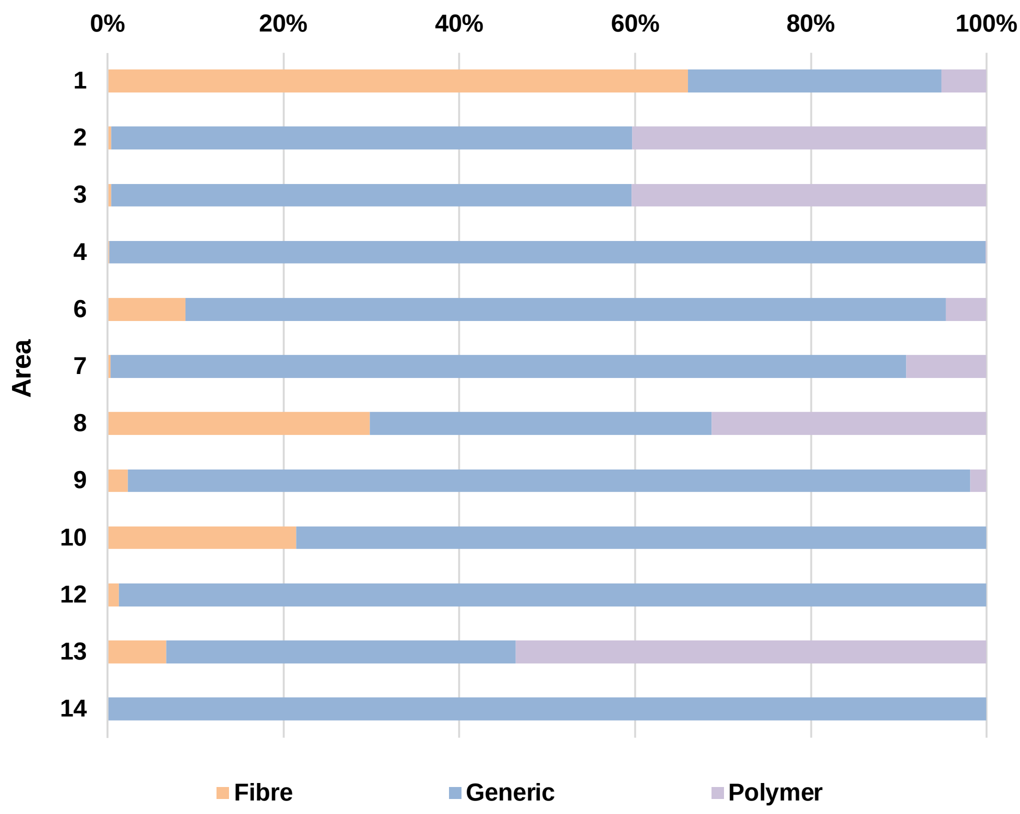

Figure 45: Proportion and Type of Thin Surface Course Systems

Figure 46 shows that 73% of all TSCS on the HE network is classified as being “generic”. 27% is recorded as incorporating polymer modified binders (17%) or fibres (10%).

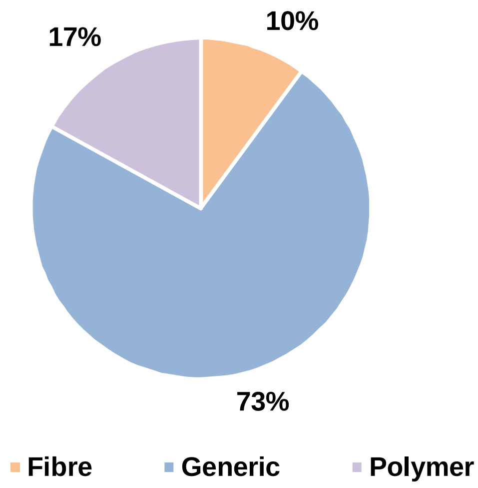

Figure 46: Summary of TSCS Types - % of Total Length across full HE Network (2012)

Data from HAPMS was summarised to indicate the thickness profile for the different areas on the SRN. This is depicted in Figure 47 and Figure 48. Figure 47 and Figure 48 shows that most areas had thickness values mostly between 20 mm – 40 mm. Evidence showed that there were very few TSCS with thickness values < 20 mm and > 50 mm on the SRN.

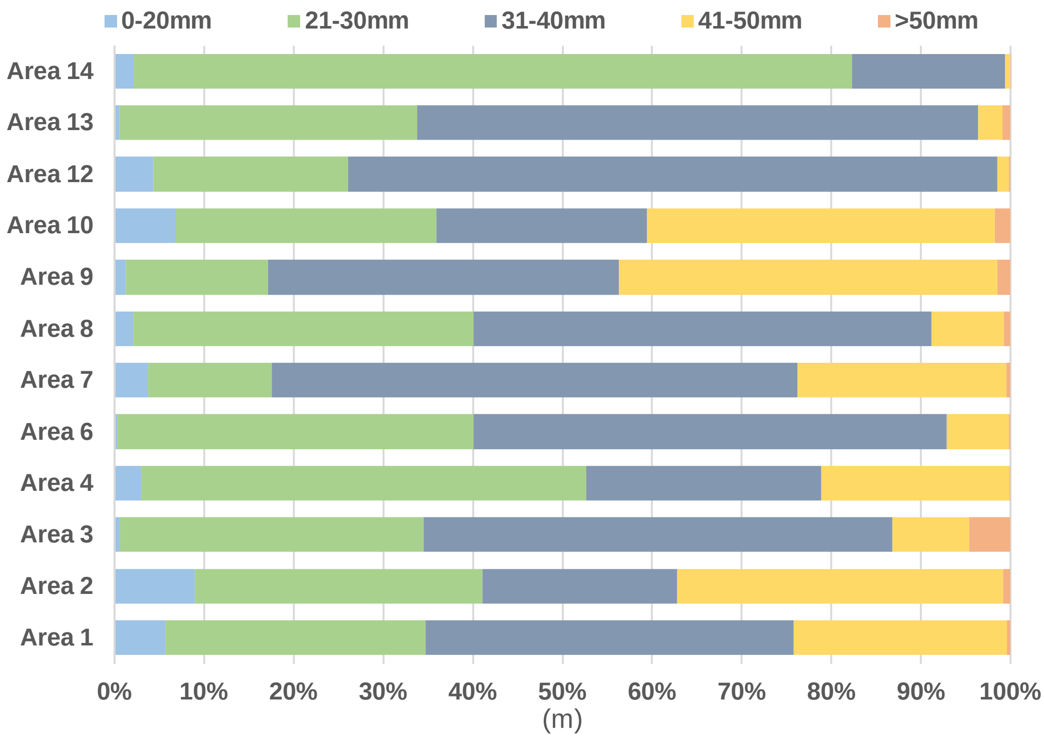

Figure 47: TSCS Thickness Profile by Length

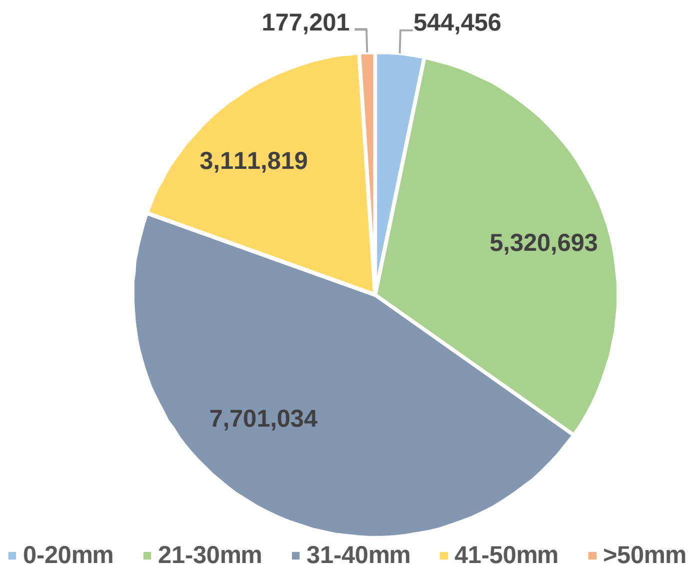

Figure 48: Total TSCS Thickness Profile on the SRN

6.3.1 Statistical Analysis

The following sections report and discuss the key relationships identified between the severity of fretting and the other parameters forming part of this analysis.

To understand the meaningfulness of results, statistical analyses were carried out. Two statistical methods were used:

- T-test analysis
- Regression analysis

The T-test is a hypothesis test, which uses sample data to test a hypothesis about the population from which the sample was taken. This test is typically used to make inferences about one or more populations when sample data are available (Minitab Inc., 2010).
In this work, the two-sample T-test ($\alpha = 0.05$) was used to determine whether two population means are different. The test uses the sample standard deviations to estimate the variability for each population.

The first step of a hypothesis test is to determine the null and alternative hypothesis. For this analysis, the following hypothesis were used:

- The null hypothesis, H_0, was that the mean of the group X (of a specific parameter) is equal to the mean of the group X (of a specific parameter);
- The alternative hypothesis, H_1, was that the mean of the group X (of a specific parameter) is NOT equal to the mean of the group X (of a specific parameter).

The test statistic is $T = \frac{\overline{X_1} - \overline{X_2}}{s_P\sqrt{\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}$, where S_P^2 is the pooled estimator of the common variance. The null distribution of T is $t(n_1 + n_2 - 2)$. Table 35 below provides a rough guide to interpreting the significance probabilities obtained from this distribution.

This method helped to evaluate whether there is enough evidence to conclude that different groups/categories of a specific parameter (e.g. TSCS having Air Voids <6% and Air Voids >6%) had a different influence on another parameter (e.g. TSCS Level of Fretting).

The discrimination power for each device are summarised in Table 35.

Table 35. T-test Results Interpretation

Significance probability	Rough Interpretation
$p > 0.10$	Little evidence against H_0
$0.10 \geq p > 0.05$	Weak evidence against H_0
$0.05 \geq p > 0.01$	Moderate evidence against H_0
$p \leq 0.01$	Strong evidence against H_0

Regression analysis is a powerful statistical method for estimating the relationships between a dependent variable and one or more independent variables.

The two basic types of regression are simple linear regression and multiple linear regression, although there are non-linear regression methods for more complicated data and analysis.

Linear regression is a basic and commonly used type of predictive analysis. The simplest form of the regression equation with one dependent and one independent variable is defined by the formula y = c

+ b*x, where y = estimated dependent variable score, c = constant, b = regression coefficient, and x = score on the independent variable. (Statistics Solutions, 2013).

Regression analysis was in this work to understand relationships between one dependent variable (e.g. Stiffness) and one independent variable (e.g. Age). The results of these analyses can be used to determining the strength of predictors, forecasting an effect, and trend forecasting.

6.3.2 Relationship of Air Voids on Level of Fretting in TSCS

Figure 49 shows that the severity of fretting increases with high air void contents. Table 36 reports the P-value results matrix, showing the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

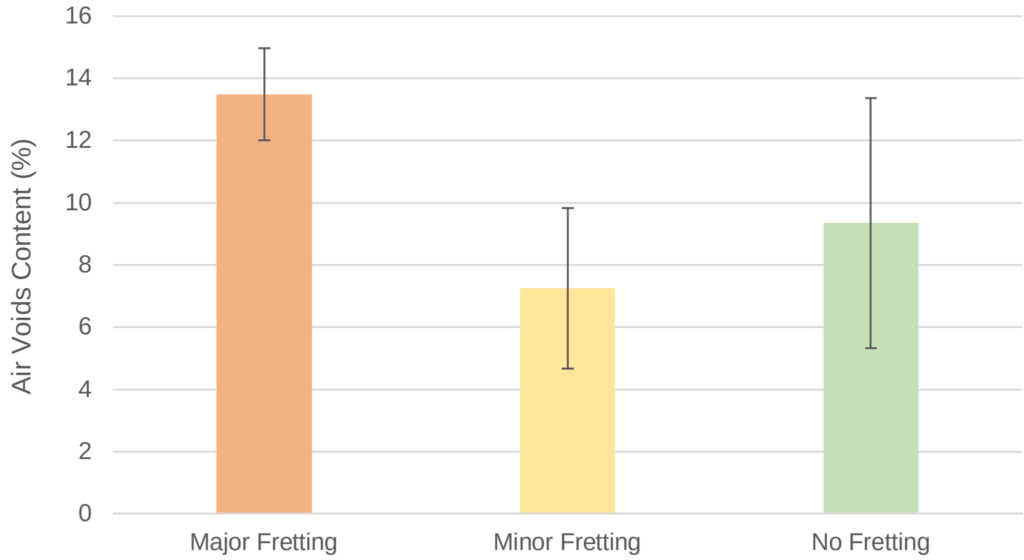

Figure 49: Relationship of Air Voids on Level of Fretting in TSCS

Table 36. Air Voids and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.000	0.000
Minor Fretting	-	-	0.052
No Fretting	-	-	-

Results reported in Table 36 show that:

When comparing Major Fretting vs Minor Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Major Fretting vs No Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Minor Fretting vs No Fretting means, there is weak evidence against the null hypothesis; thus, the two means are comparable.

Figure 50 shows that samples with air void contents > 12% had evidence of major fretting (67%). The samples with air void contents < 6% had evidence of no fretting.

The results from Figure 49 and Figure 50 are in line with previous research reports stating that mixtures are susceptible to fretting if the air void content is high. High air void contents also increase the permeability of the layer to air and water which makes the asphalt prone to stripping adversely impacting on the overall performance and durability of the TSCS (Willway et al., 2008; Khojinian, Parry and Thom, 2016; ZTV Asphalt, 2017; StB, 2017).

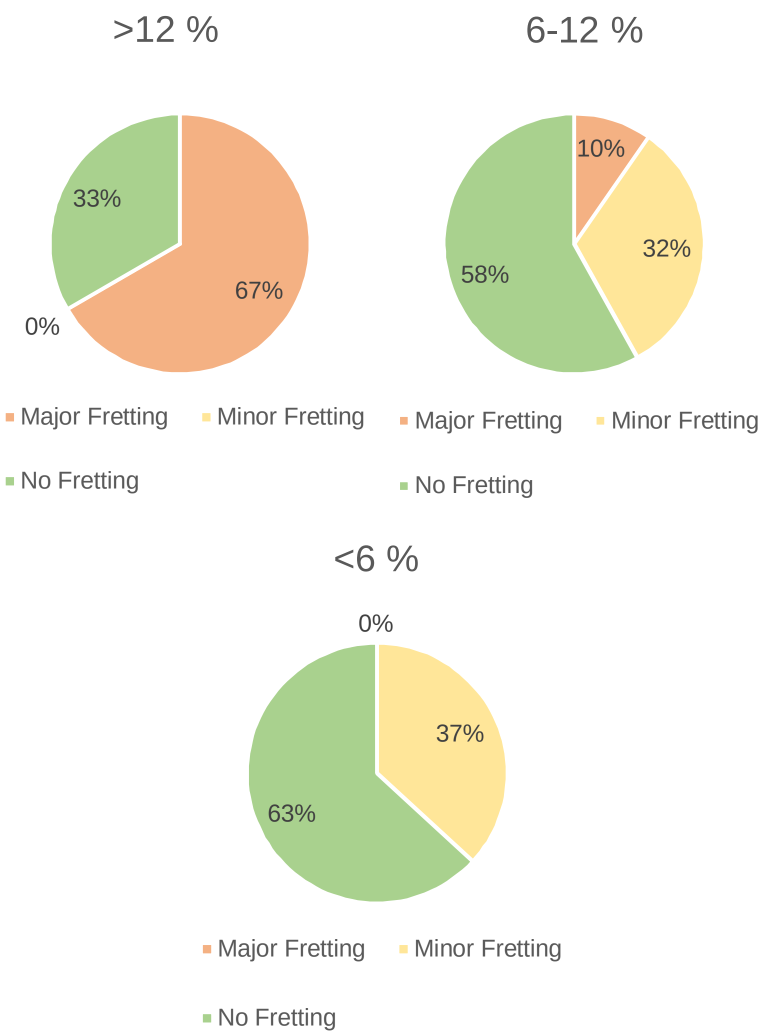

Figure 50: Air Voids on Level of Fretting

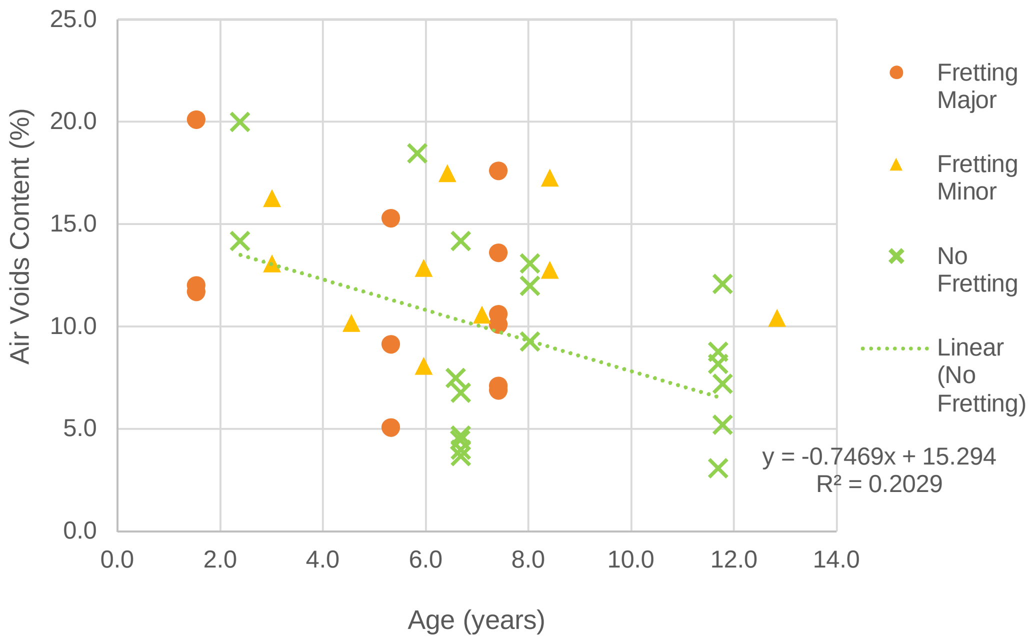

Figure 51: Relationship of Air Voids Content on Age

Figure 51 shows that nearly all sites with the air void content of greater than 6% were within the Major fretting category. All the sites with Major fretting needed to be resurfaced by year 7. In contrast a significant portion of sites with No fretting had air void content of less than 10%. The regression line of No Fretting values shows that there is a correlation between Age and Air Voids of TSCS, lower voids corresponding to older materials.

All those sites demonstrated a higher number of years in service before needing to be resurfaced.

6.3.3 Relationship of Texture Depths on Level of Fretting in TSCS

Figure 52 shows the relationship of texture on the level of fretting in TSCS. Figure 52 indicates that higher levels of fretting could result in increased texture depth measurements. Viner et al (2006) stated that fretting might increase texture depth further due to the gaps left by lost aggregates.

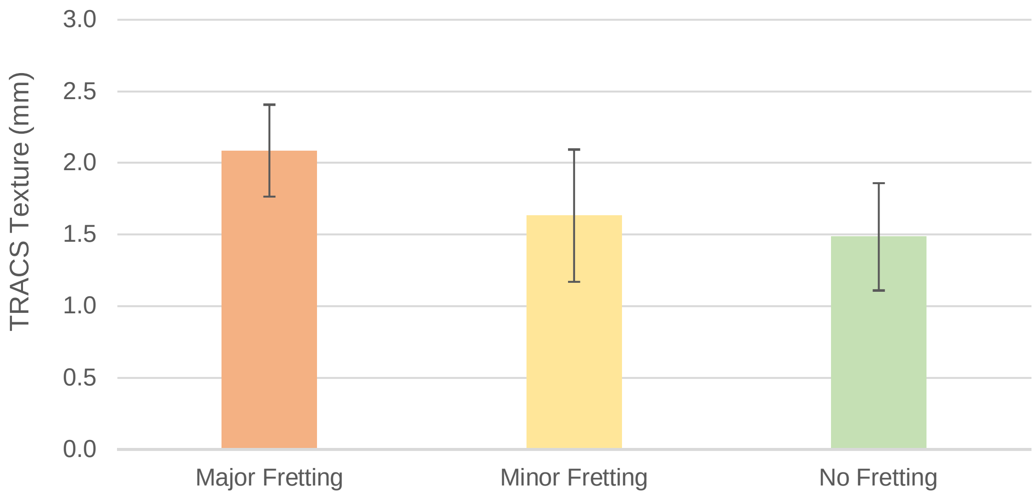

Figure 52: Relationship of TRACS Texture on Level of Fretting in TSCS

Table 37 reports the P-value results matrix, showing the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

Table 37. TRACS Texture and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.001	0.000
Minor Fretting	-	-	0.220
No Fretting	-	-	-

Results reported in Table 37 show that:

When comparing Major Fretting vs Minor Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Major Fretting vs No Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Minor Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

Figure 53 shows that most samples with texture depth values > 1.5 mm (50%) experienced major fretting and 22% of samples had minor fretting. Figure 53 shows that 76% of samples with texture depth values <1.5 mm had no fretting. The results in Figure 52 and Figure 53 are in line with experience in the field and in previous research (Viner et al., 2006; Khojinian, Parry and Thom, 2016; ZTV Asphalt, 2017; StB, 2017).

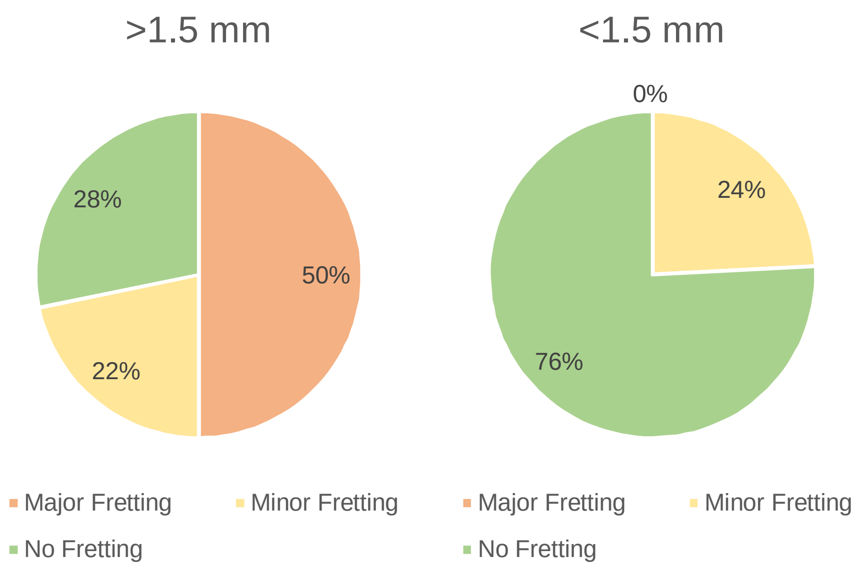

Figure 53: Texture Depth on Level of Fretting

Further to analysis as detailed in Figure 52 and Figure 53, an evaluation to obtain the relationship between texture depth values and air void content was conducted. The results in Figure 54 show that major fretting is more predominant with air voids >12% and texture depth values > 2.0 mm.

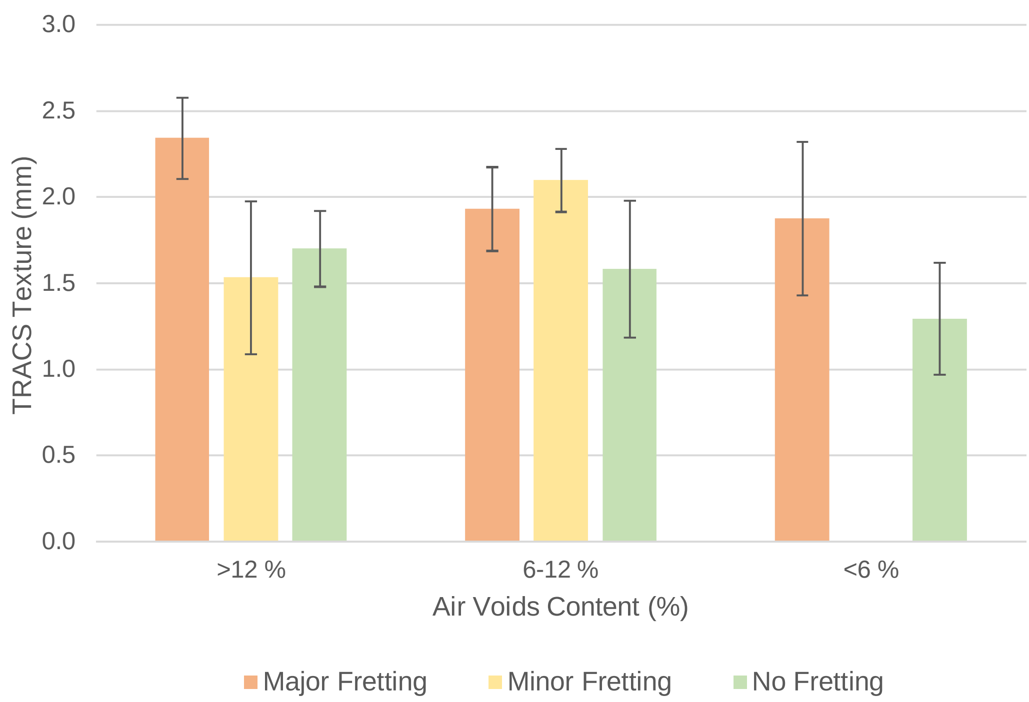

Figure 54: Relationship between Texture Depth Values and Air Void Content

6.3.4 Relationship of Aggregate Nominal Size on Fretting of TSCS

The relationship of aggregate nominal size on the fretting of TSCS was evaluated as part of this study. The results are presented in Figure 55. The results indicate that TSCS manufactured using 10 mm aggregate nominal size had no signs of major fretting in comparison to the use of 14 mm aggregate nominal size with 87% showing minor and major fretting. McHale, Carswell and Poe (2006) provided details stating that smaller aggregate nominal sizes (0/10 mm and 0/6 mm) were considered unable to routinely meet the required texture depth specifications.

The use of 14 mm aggregate nominal size tends to produce a more open texture asphalt with higher air voids. These characteristics result in mixtures that are prone to fretting (Viner et al., 2006; Khojinian, Parry and Thom, 2016; StB, 2017).

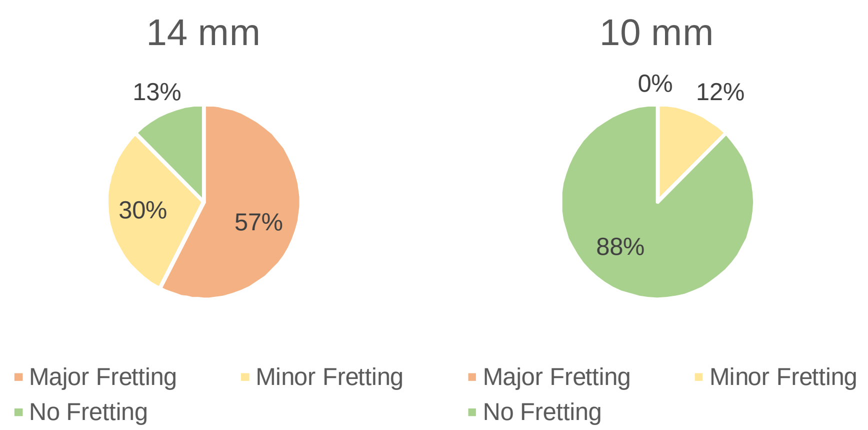

Figure 55: Relationship of Aggregate Nominal Size on Fretting of TSCS

Figure 56 shows that most sites with nominal size aggregate of 10 mm generally had air void content of less than 8.5%. This in conjunction with the finding from Figure 55 demonstrates that a 10 mm size aggregate with lower void content had outperformed the sites with 14 mm size aggregate where they had higher air voids.

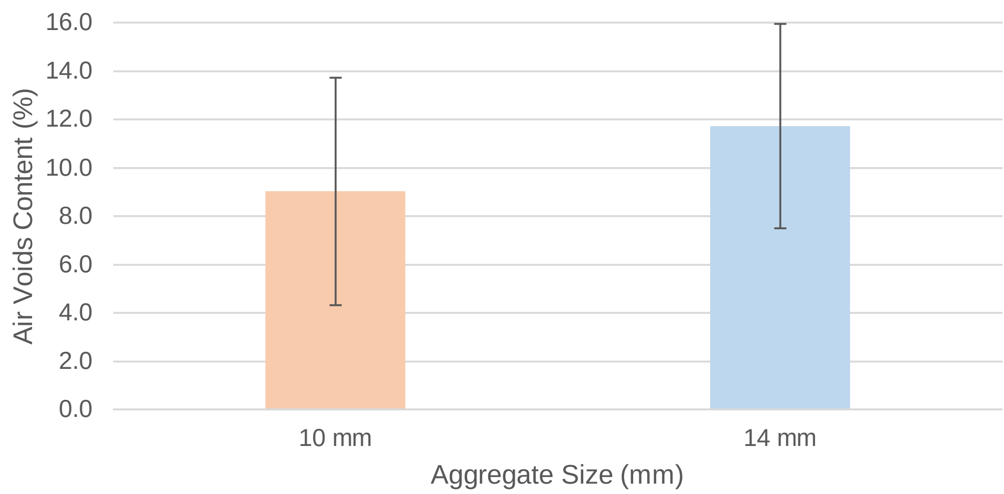

Figure 56: Relationship of Aggregate Nominal Size on Air Voids

In order to evaluate if there is sufficient evidence (due to the relatively high standard deviation) to conclude that 10 mm and 14 mm TSCS have different air voids (AV), a T-test was run:

The null hypothesis, H_0, was that 10 mm AV mean is equal to 14 mm AV mean.
The alternative hypothesis, H_1, was that 10 mm AV mean is equal to 14 mm AV mean.

The result showed a P-value of 0.000, indicating that there is strong evidence against H_0. In other words, 10 mm and 14 mm TSCS have different air voids (AV).

6.3.5 Relationship of Stiffness on Fretting

Figure 57 shows that sites categorised with major fretting generally have lower average stiffness values.

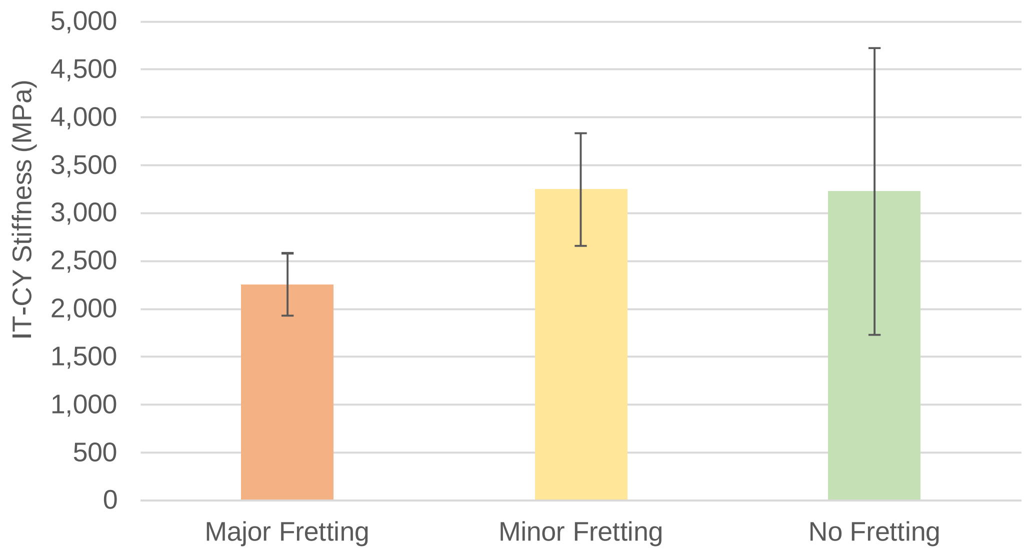

Figure 57: Relationship of Stiffness on Fretting

Table 38 reports the P-value results matrix, showing the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

Table 38. IT-CY Stiffness and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.000	0.000
Minor Fretting	-	-	0.237
No Fretting	-	-	-

Results reported in Table 38 show that:

When comparing Major Fretting vs Minor Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Major Fretting vs No Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Minor Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

Figure 58 shows that most sites with No Fretting or Minor Fretting have a high stiffness value greater than 3000 MPa. All sites with Major Fretting have a stiffness below this value. Overall, there is a fair correlation between the age and the stiffness of the samples, the older TSCS being stiffer. This is attributed to the hardening of the binder due to weathering as well as to the densification of the asphalt and it is in line with general expectations.

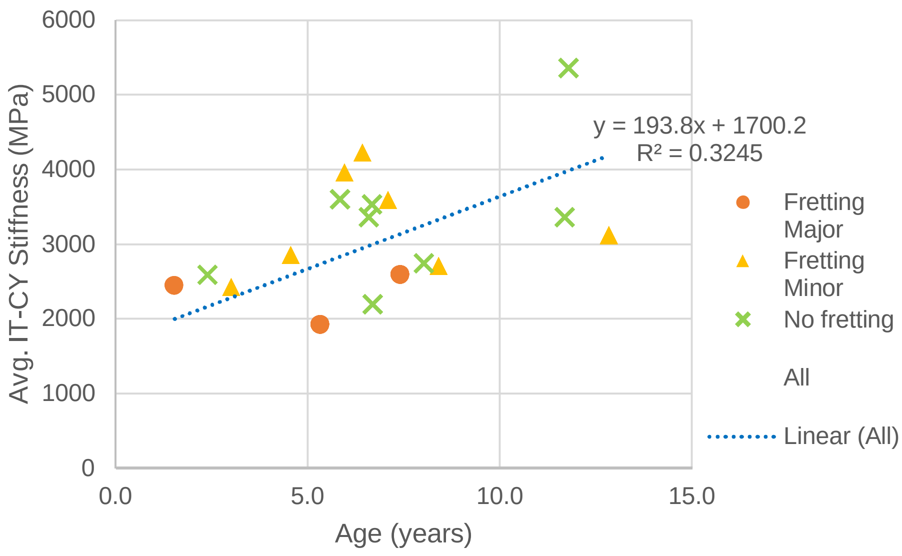

Figure 58: Relationship of Stiffness on Age

6.3.6 Relationship of Binder Content on Fretting of TSCS

Figure 59 and 60 show that there is no clear relationship between the influence of binder content and fretting of TSCS. The data showed that the estimated binder content ranges between 5% and 6% for the TSCS sites evaluated. In comparison to other European countries where the binder content for a typical SMA is considerably higher as detailed in Section 3.7. Considering this factor, there were no clear relationship as some TSCS with lower binder contents outperformed other TSCS with higher binder contents.

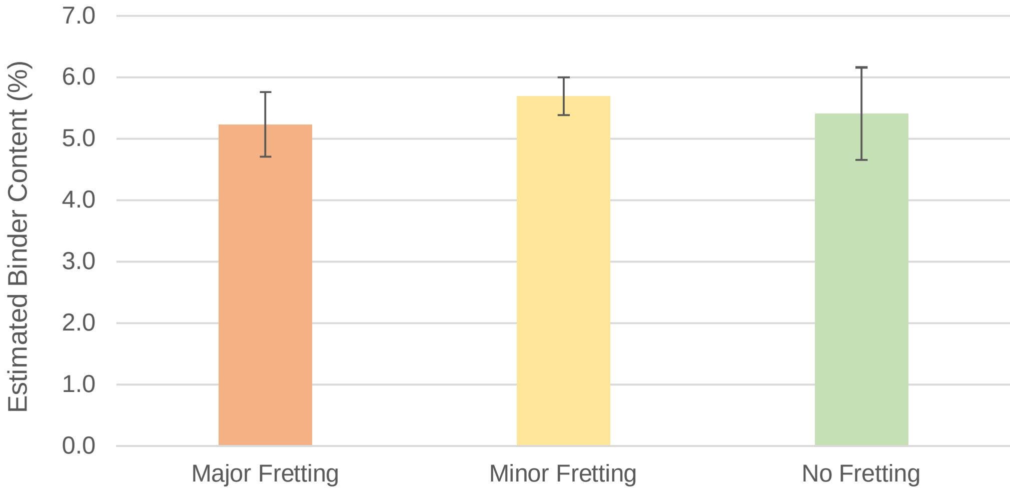

Figure 59: Relationship of Binder Content on Fretting

Table 39 reports the P-value results matrix, showing the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

Table 39. Binder content and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.007	0.431
Minor Fretting	-	-	0.176
No Fretting	-	-	-

Results reported in Table 39 show that:

When comparing Major Fretting vs Minor Fretting means, there is strong evidence against the null hypothesis, thus, the two means are different.

When comparing Major Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

When comparing Minor Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

Statistical results confirm that there is no clear relationship between the binder content and the Level of Fretting.

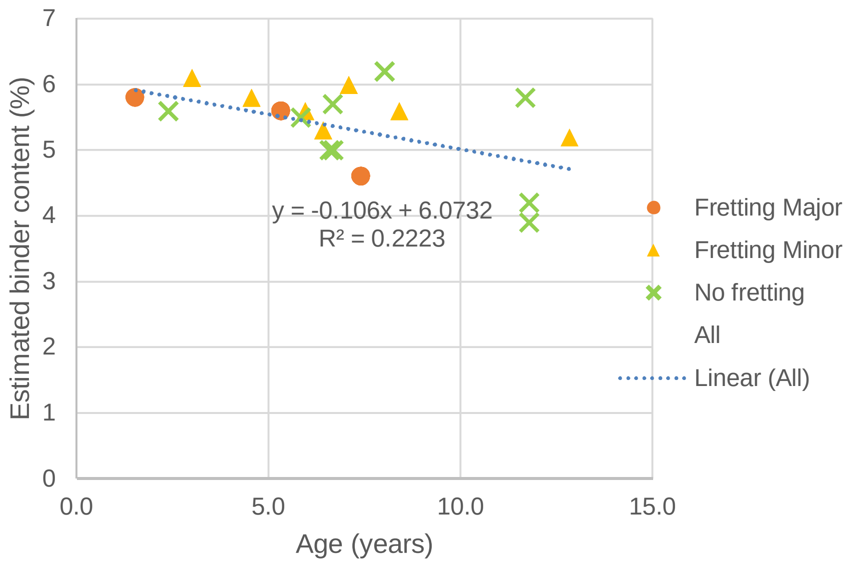

Figure 60: Relationship of Binder Content on Age

Figure 60 trendline shows that the binder content slightly decreases with the age of the binder. Assuming similar content when laid for all TSCS, this might indicate stripping of the aggregate due to traffic and/or environmental factors.

6.3.7 Relationship of Penetration on Fretting of TSCS

Figure 61 reports average results of DSR Penetration for samples belonging to the categories ‘Major Fretting’, ‘Minor Fretting’ and ‘No Fretting’. The standard deviations are included as error bars in the chart.

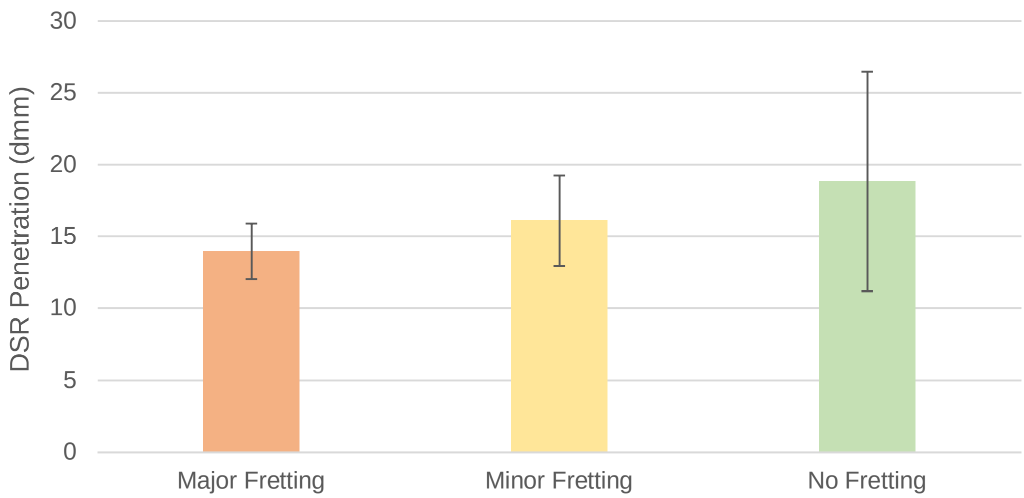

Figure 61: Relationship of Penetration on Fretting of TSCS

In order to understand the statistical significance of these results, Table 40 reports the P-value results matrix. This shows the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

Table 40. Penetration and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.011	0.004
Minor Fretting	-	-	0.165
No Fretting	-	-	-

Results reported in Table 40 show that:

When comparing Major Fretting vs Minor Fretting means, there is moderate evidence against the null hypothesis, thus, the two means are reasonably different.

When comparing Major Fretting vs No Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Minor Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

Results from Figure 61 and Table 40 indicate that higher level of fretting of TSCS are associated to low binder penetration values. This is in agreement with Willway et al. (2008), who noted that low penetration values associated with age hardening resulting in increased brittleness of the binder matrix, crack formation and fretting.

6.3.8 Relationship of Fibres

Figure 62 shows that most samples with fibres incorporated in the TSCS experienced minor and major fretting. The sites with no fibres had no major fretting. It was noted that other factors such as the air void content, binder content and age of the TSCS could be contributing to this phenomenon. It should be noted that factors contributing to cause and/or accelerate fretting are often interdependent. Therefore, further studies are required to ascertain if there are any adverse impacts of fibres on the fretting of TSCS.

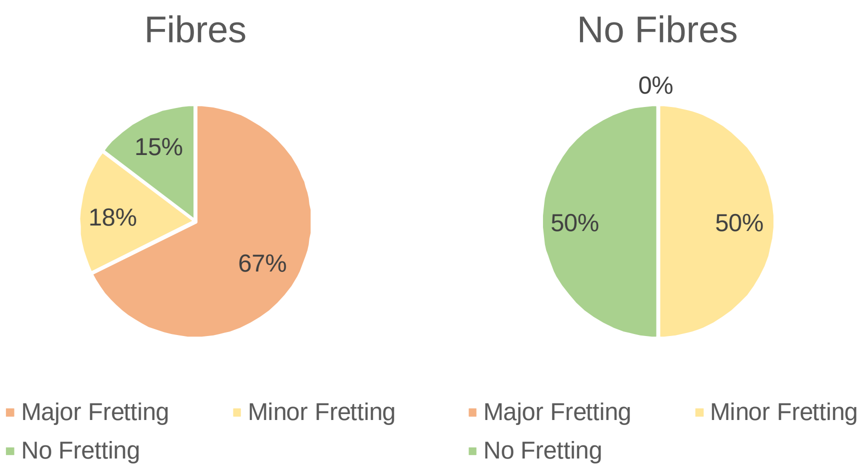

Figure 62: Relationship of Fibres

6.3.9 Relationship of Layer Thickness on Fretting

Figure 63 presents the findings on the influence of layer thickness on the fretting of TSCS obtained from the HAPMS database. Figure 63 indicates that majority of samples (61%) with TSCS layer thickness > 40 mm had no fretting. The analysis showed an even split between no fretting and major fretting for samples with layer thickness < 40 mm.

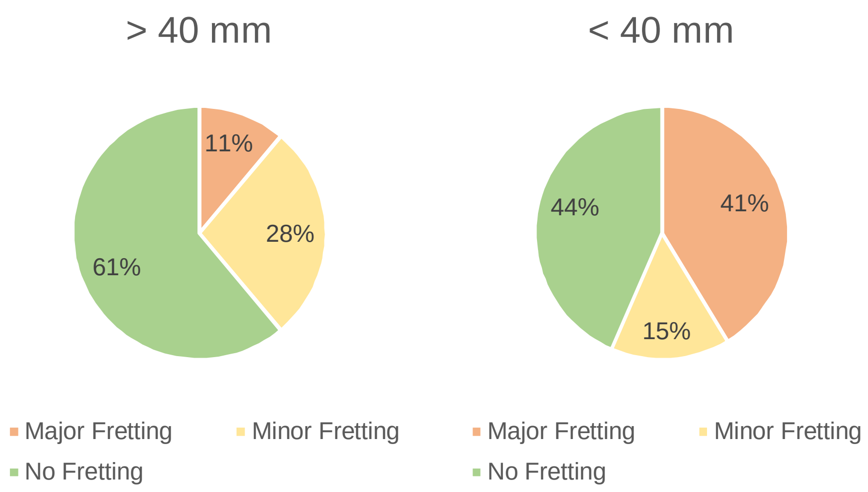

Figure 63: Relationship of Layer Thickness on Fretting

Figure 64 shows that all samples with Major fretting were laid thinner than 40mm. The samples with thickness greater than 40mm did not have Major fretting. However, there is no clear correlation found between the thickness of TSCS and fretting, as some sites laid thinner than 40mm performed well in terms of service life and fretting.

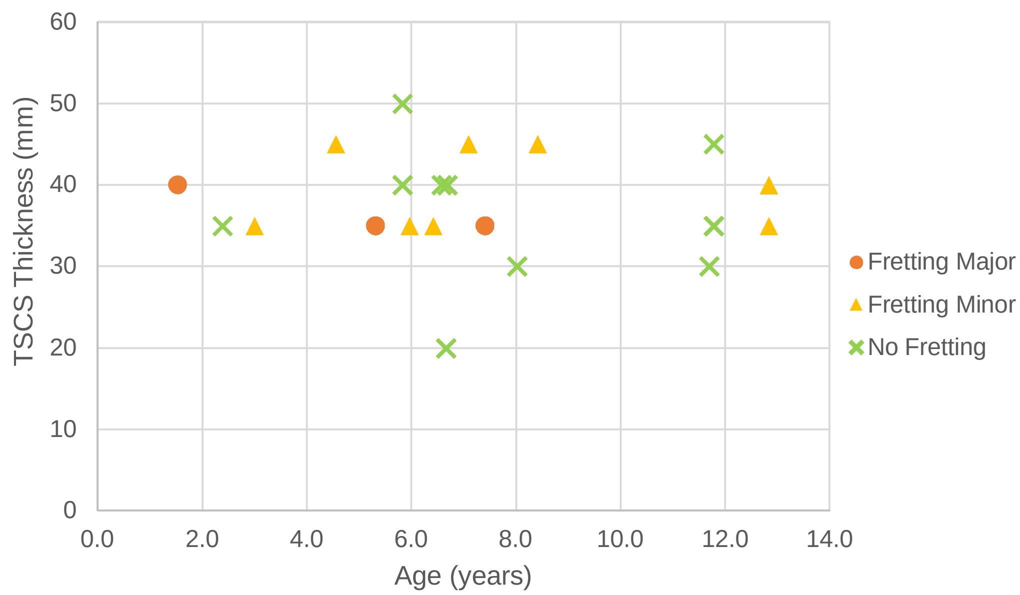

Figure 64: Layer Thickness vs Age

6.3.10 Relationship of TSCS Age on Fretting

Figure 65 presents the findings following analyses on the influence of age on fretting.

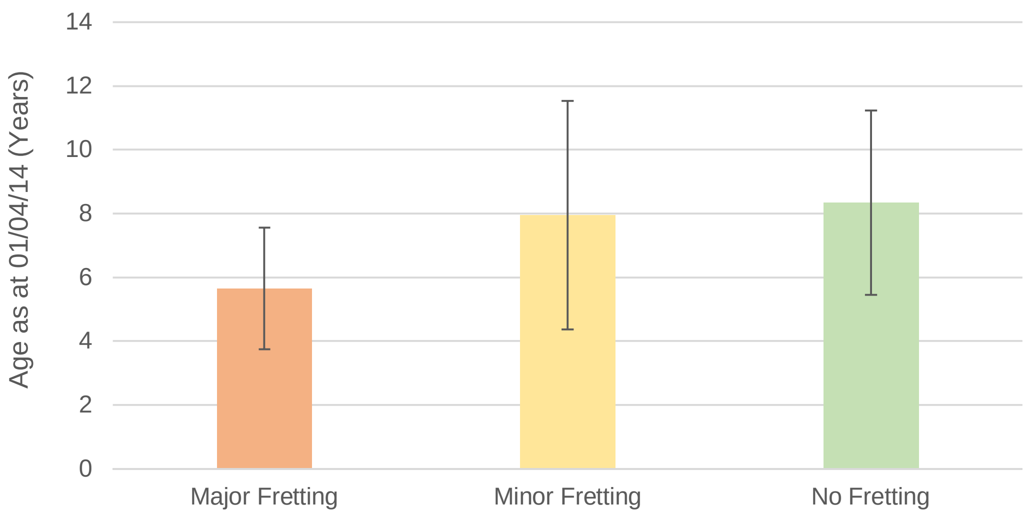

Figure 65: Relationship of TSCS Age on Fretting

In order to understand the statistical significance of these results, Table 41 reports the P-value results matrix. This shows the significance of probability (to be read in conjunction with Table 35) of two-sample T-tests carried out to each pair of Level of Fretting category: Major Fretting vs Minor Fretting; Major Fretting vs No Fretting; Minor Fretting vs No Fretting.

Table 41. Age and Level of Fretting in TSCS - T-test P-value Results Matrix

P-value	Major Fretting	Minor Fretting	No Fretting
Major Fretting	-	0.013	0.000
Minor Fretting	-	-	0.664
No Fretting	-	-	-

Results reported in Table 41 show that:

When comparing Major Fretting vs Minor Fretting means, there is moderate evidence against the null hypothesis, thus, the two means are reasonably different.

When comparing Major Fretting vs No Fretting means, there is strong evidence against the null hypothesis; thus, the two means are different.

When comparing Minor Fretting vs No Fretting means, there is little evidence against the null hypothesis; thus, the two means are not different.

Results from Figure 65 and Table 41 indicate that the level of fretting of TSCS seems not to be related to the age, as a fundamental factor. Instead, the relatively high number of samples with less presenting Major Fretting indicates that the fretting phenomenon, possibly related to poor design and/or construction, is exhibited in the short/medium-term.

6.3.11 Relationship of Heavy Goods Vehicle (HGV) on Fretting

The influence of Heavy Goods Vehicle (HGV) on fretting is presented in Figure 66 & 62. There is no clear correlation between the severity of fretting and HGV traffic levels. However, excluding those samples experiencing no fretting, higher HGV AADF corresponds more severe fretting. Considering this, research shows that increasing traffic levels can increase the severity of fretting on TSCS as detailed in (Willway et al., 2008; Khojinian, Parry and Thom, 2016; ZTV Asphalt, 2017; StB, 2017).

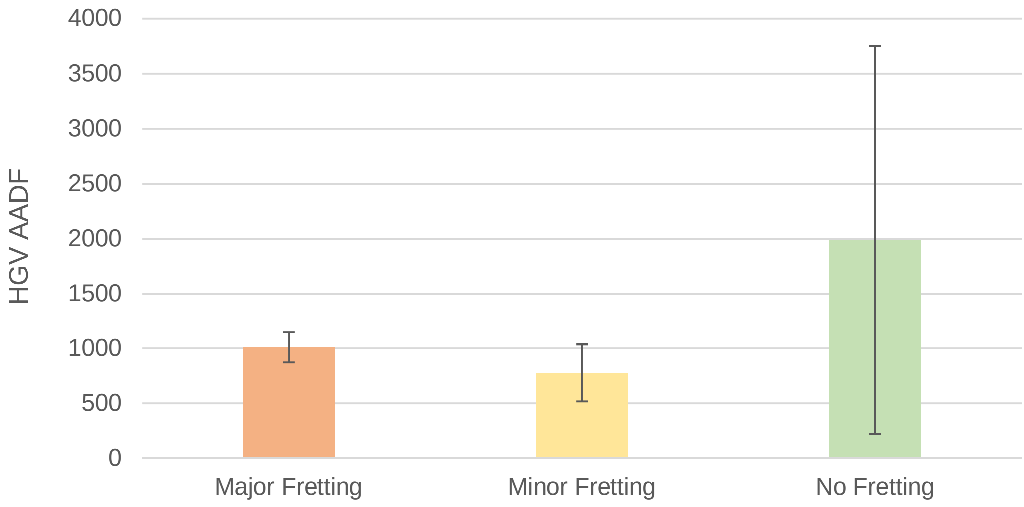

Figure 66: Relationship of Heavy Goods Vehicle (HGV) on Fretting

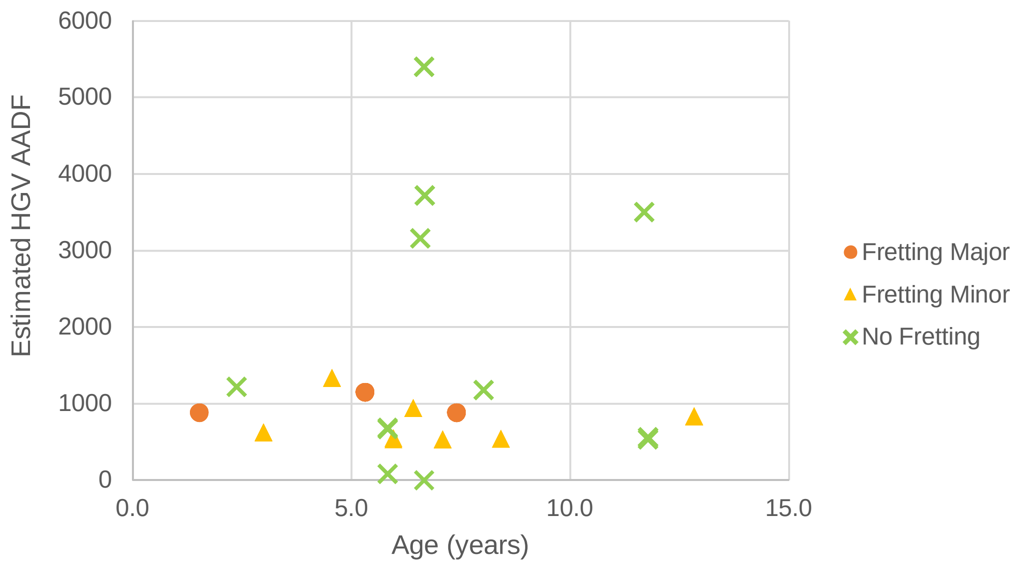

Figure 67: Relationship of Heavy Goods Vehicle (HGV) on Age

6.3.12 Relationship of Laying Season

Figure 68 shows the influence of the laying season on fretting of TSCS.

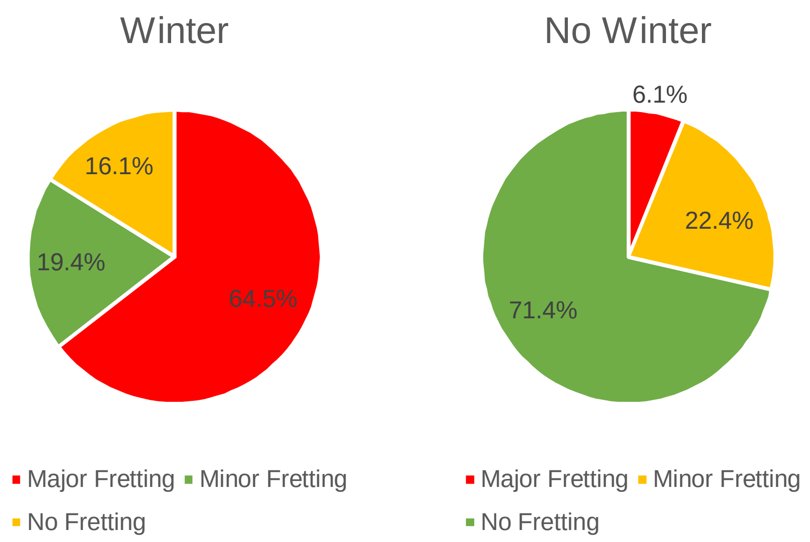

Figure 68: Relationship of Laying Season on Fretting of TSCS

Winter: November to March

No Winter: April to October

Figure 68 shows that when the TSCS were laid in winter, the number of sites that showed major fretting was 64.5% and 19.4% of sites had minor fretting in comparison to 16.1% of sites with no fretting. 71% of the TSCS sites not installed in winter had no fretting, 22.4% had minor fretting with only 6.1% showing signs of major fretting.

This information shows the importance of laying seasons for the installation of TSCS. Figure 69 shows the laying seasons for the different network areas between April 2017 and March 2018. Figure 70 summarises the information indicating that currently 54% of TSCS is installed in the winter period.

Figure 69: Length (%) of TSCS laid in Winter/No Winter (April 2017 - March 2018)

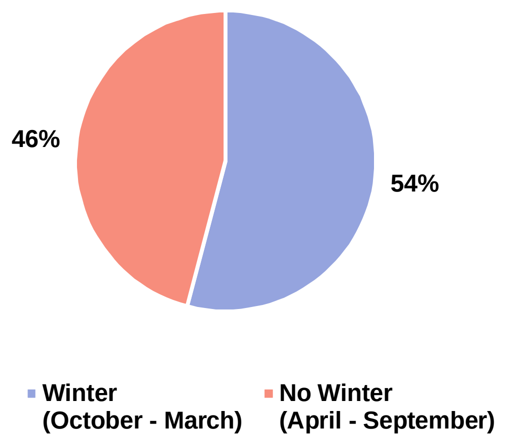

Figure 70: Proportion of TSCS Laid in Winter/No Winter

6.4 Detailed Analysis Using Viscous to Elastic Transition (VET) Temperature

Current standards and specifications for TSCS have no requirement for binder rheology to provide an indication of surface condition to help monitor surfacing deterioration. The current Value Management (VM) requirements are based on a life expectancy of TSCS.

TSCS with more than ten years in service are usually marked for resurfacing irrespective of condition. This approach does not seem to be the most efficient and cost-effective approach to managing the network as there are questions as to why a TSCS needs to be resurfaced if there are no defects present.

The concept of Viscous to Elastic Transition (VET) temperature is detailed in Section 4.5 of this report. VET analysis provides a unique approach to using rheological properties to establish how fretting and dynamic changes in bituminous materials are associated. The analyses consider the impact of different levels of age hardening and distress levels.

VET analysis was carried out on recovered bitumen in accordance with BS EN 12697-3 and binder rheology using the DSR in accordance with EN 14770 from all sites investigated in this research. The results and analysis are discussed in this section of the report. The VET analysis is characterised by 3 key zones: “Critical”, “Buffer” and “As Expected/Sound”.

These zones were devised as part of this study and in line with the principles of the VET. Table 42 presents an interpretation of the zones as shown in the VET graphs/charts for this section. The subsequent sections of this chapter provide important discussions of findings.

Table 42: Proposed interpretation of the Zones Used in the VET Analysis

Zone	T_{VET}	G^*_{VET}	Surface Condition
Critical Zone	Greater than 20ºC and	Lower than 10 MPa	Severely age-hardened material with high risk for fretting.
Buffer Zone	Greater than 17ºC and	Lower than 12.5 MPa (excluding the Critical Zone)	Age-hardened material with increasing risk for fretting.
As Expected/ Sound Zone	Lower than 17ºC	Greater than 12.5 MPa	Material with limited age-hardening and low risk for fretting.

6.4.1 Identifying Fretting Using VET Analysis

Figure 71 presents findings using VET analysis to identify sites by level of fretting. Figure 71 shows that all samples identified as “Major Fretting” fall within the “Critical Zone”. This is as expected with the fretted samples attributed to poor site conditions, sites with surface cracks or sites where material losses have been observed during visual condition surveys.

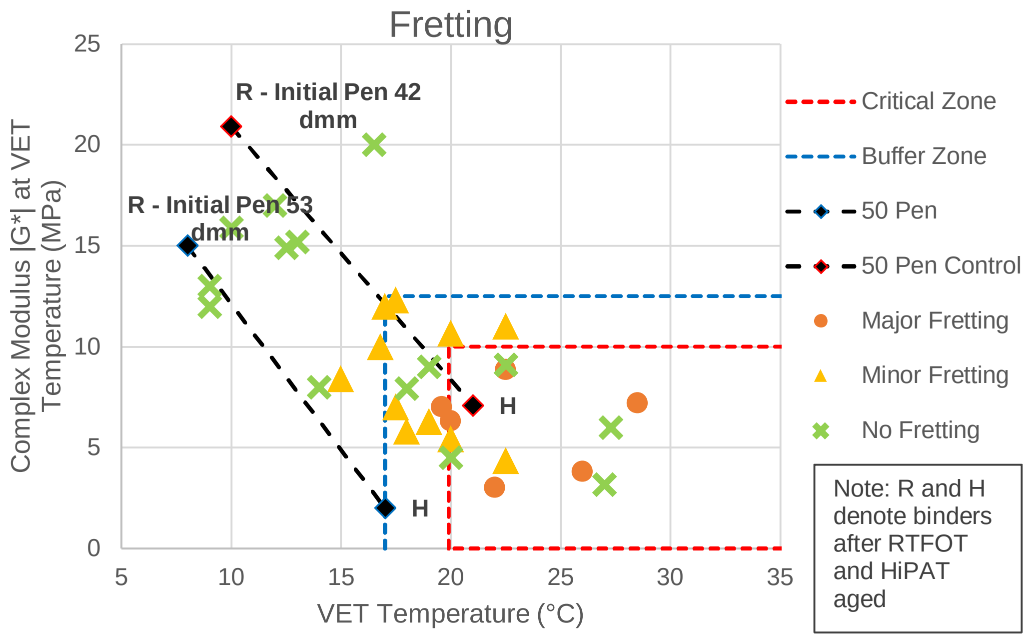

Figure 71: Identifying Fretting Using VET Analysis

The samples categorised as “Minor Fretting” were mostly (64%) in the “Buffer Zone” as depicted in Figure 71. The samples indicated age-hardening with increased risk for cracking or material loss of the TSCS (Widyatmoko et al., 2004). Close monitoring is required for these TSCS. The distribution of samples categorised as showing no signs of fretting “No Fretting” are detailed in Figure 71. These samples were mostly out of the “Critical” and “Buffer” Zones. As detailed in Figure 72, 57% of the samples were in the expected regions as shown on the T_{VET} against their respective complex stiffness modulus, G^*_{VET} plots in Figure 71. 14% were in the “Buffer Zone” indicating increased susceptibility to fretting, attributed to poor site conditions, sites with surface cracks or sites where material losses have been observed. The samples in the “critical” zones need to be reviewed further to ascertain if other factors are influencing the performance of the TSCS.

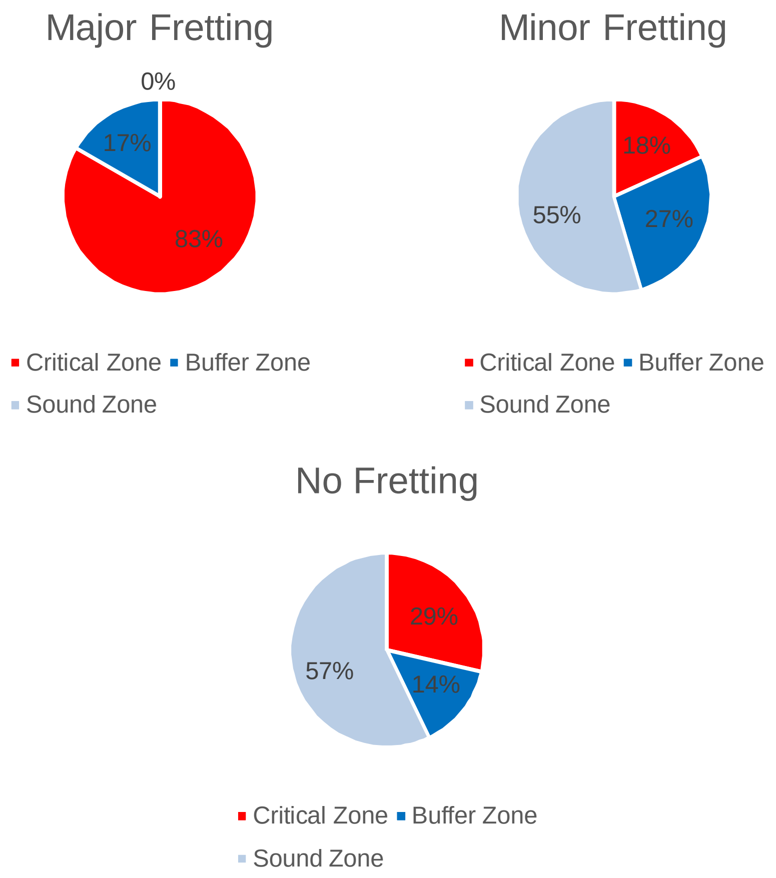

Figure 72: Proportion of Sites Categorised as “Major”, “Minor” or “No Fretting”

6.4.2 VET Analysis Categorised Based on Penetration

The samples were categorised considering the penetration values which details the consistency of a bituminous material at a given temperature. The classification used comprised of the following as detailed below:

1. Samples with penetration ≤13 dmm
2. Samples with penetration ranging between 13 – 20 dmm
3. Samples with penetration ≥ 20 dmm

The test results are presented in Figure 73.

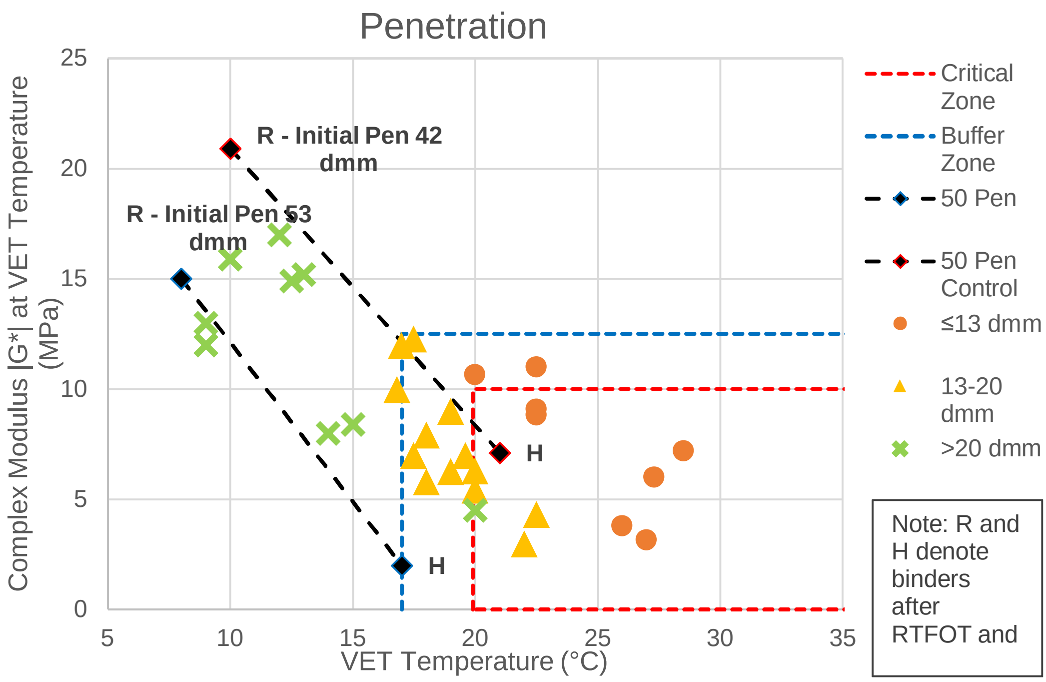

Figure 73: VET Analysis Categorised Based on Penetration

Figure 73 indicates that reduced penetration values are directly related to ageing and a reduction in the visco-elastic properties of the bitumen. All samples ≤ 13 dmm were in the “Critical Zone” or the “Buffer Zone”.

The samples with penetration values in the range 13 dmm – 20 dmm were mostly within the “Buffer Zone” with two sites in the “Critical Zones”.

This is expected due to age-hardening with an increased risk for cracking or material loss. The samples with penetration values ≥ 20 dmm were generally outside the “Critical and Buffer Zones” as presented in Figure 73. These materials are usually in sound condition with low to moderate risk of cracking. This exercise shows a good relationship with the VET analysis and observations Figure 71. All the specimens from sites with No Fretting that appear in the critical zone in Figure 66, are seen to have low or intermediate pen in Figure 74. Figure 74 shows that there is a consistent distribution of each group of penetration into the three zones. The majority (75%) of points having ≤ 13 dmm are in the “Critical Zone” and 25% of the samples in the “Buffer

Zone”. Figure 74 shows that the majority (89%) of the points having ≥ 20 dmm falls in the “Sound/ As Expected” Zone. The majority (61%) of the points having 13-20 dmm are in the “Buffer Zone”. These results are in line with expectations: critical VET parameters are associated with low penetration values.

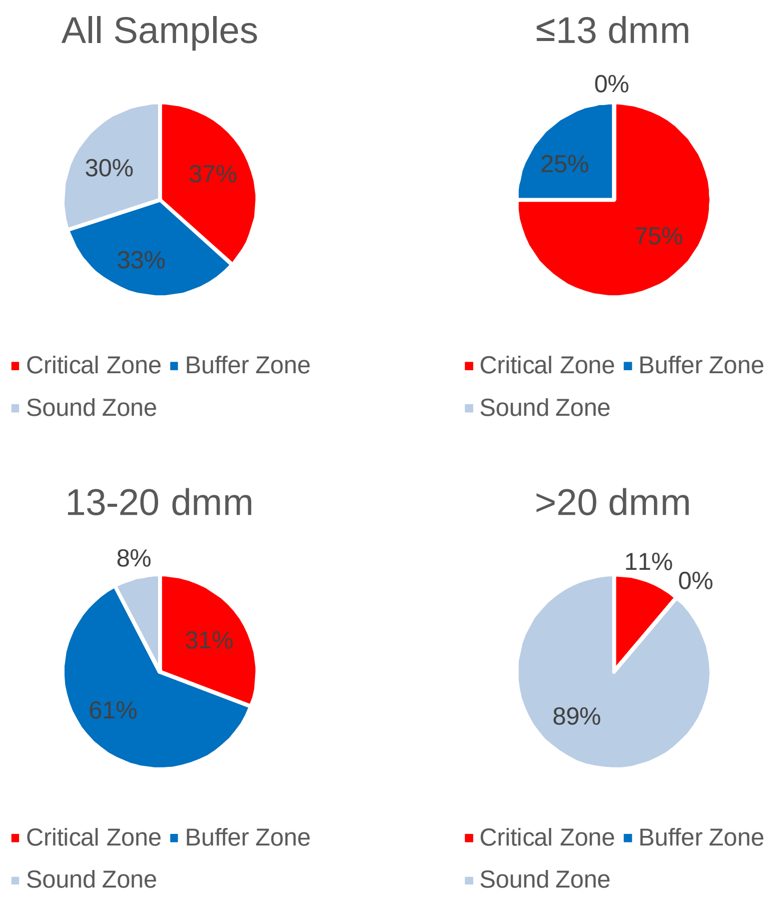

Figure 74: Analysis of Findings on VET Analysis for Penetration Values

6.4.3 VET Analysis Categorised Based on Air Voids

The samples were categorised based on air voids as detailed below:

1. < 6%
2. 6% - 12%
3. > 12%

Figure 75 shows that increased air voids content is associated with samples in both the “Buffer Zone” and “Critical Zone”. This was evident as seen on samples with high air void contents categorised as > 12%. Low voided samples < 6% were mostly outside the “Buffer and Critical Zones” with two samples in the critical zone. The two samples in the “Critical Zone” had penetration values < 13 dmm as presented in Figure 73.

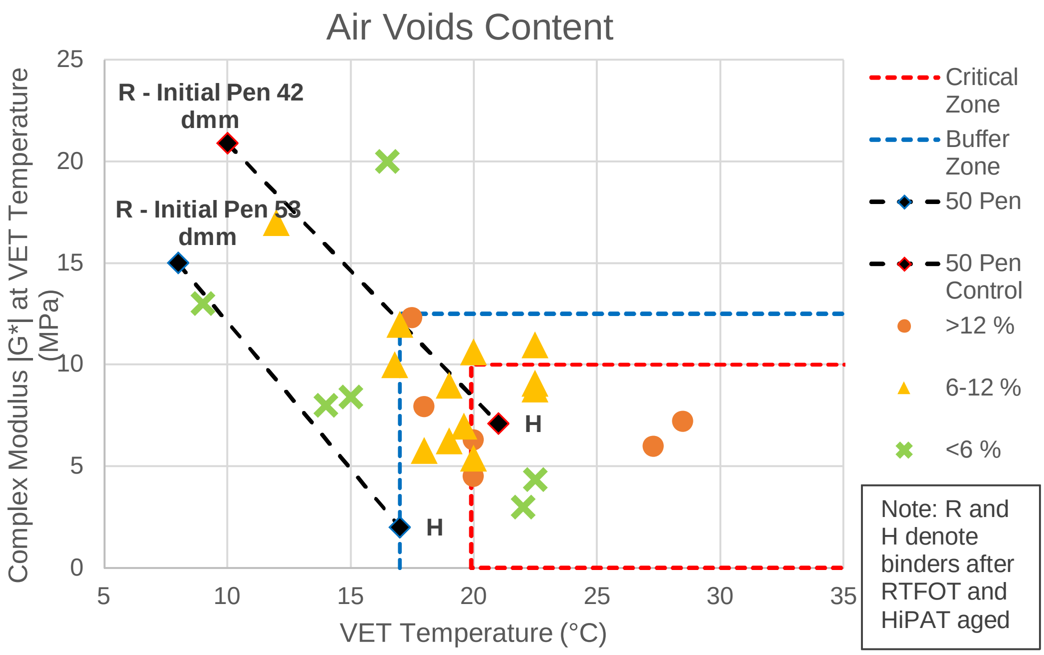

Figure 75: VET Analysis Categorised Based on Air Voids Content

6.4.4 VET Analysis Categorised Based on Age

Figure 76 presents findings using the VET analysis categorised based on age.

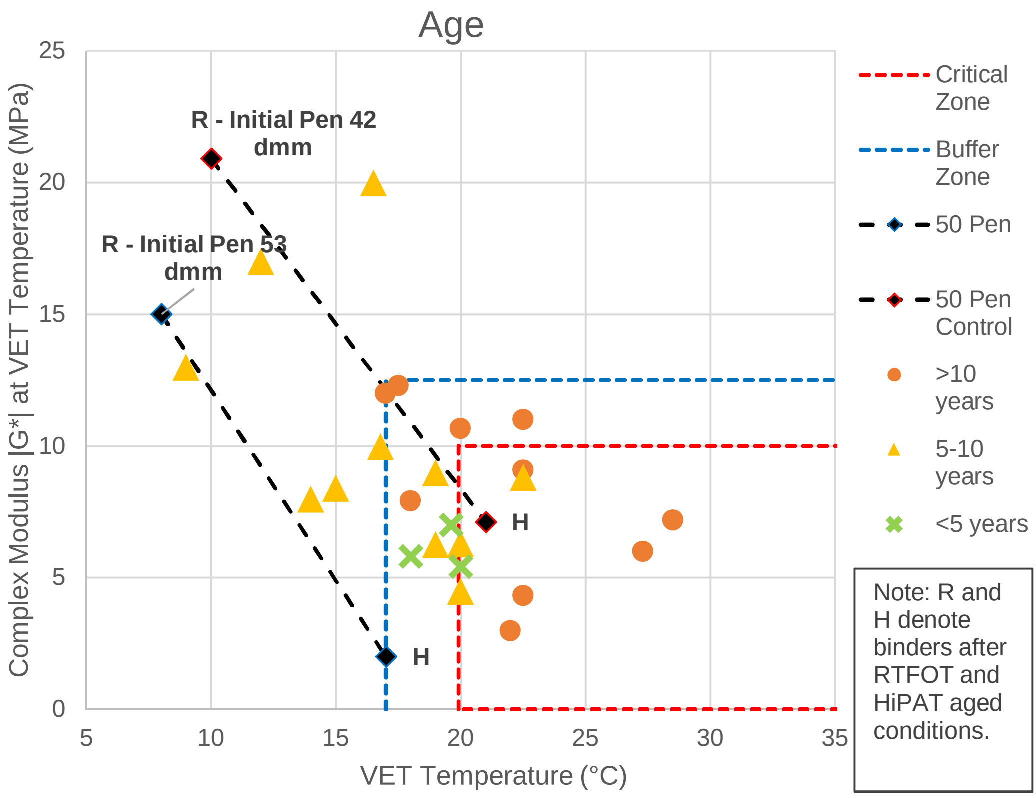

Figure 76: VET Analysis Categorised Based on Age

The age range comprised of the following:

- < 5 years
- 5 – 10 years
- > 10 years

Figure 76 shows that samples > 10 years of age were mostly in the "Critical" and "Buffer" Zones. The proportion of samples in the "Critical" and "Buffer" Zones were split 50% as seen in Figure 77.

The samples in the "Critical" and "Buffer" Zones indicate samples that are severely age-hardened material with a high risk for cracking or material loss. Possible close monitoring and possibly preventive maintenance should be considered for these sites.

Samples between 5 – 10 years had presence in all zones of the graph as expected with samples in the “Critical Zone”, “Buffer Zone” and “Sound Zones”. The samples < 5 years were in the buffer zone. These samples had a result which could be due to other factors such as reduced penetration (<13 dmm), low air voids. Other factors could be attributed to construction issues on site (laying, compaction, weather). These samples should be reviewed further.

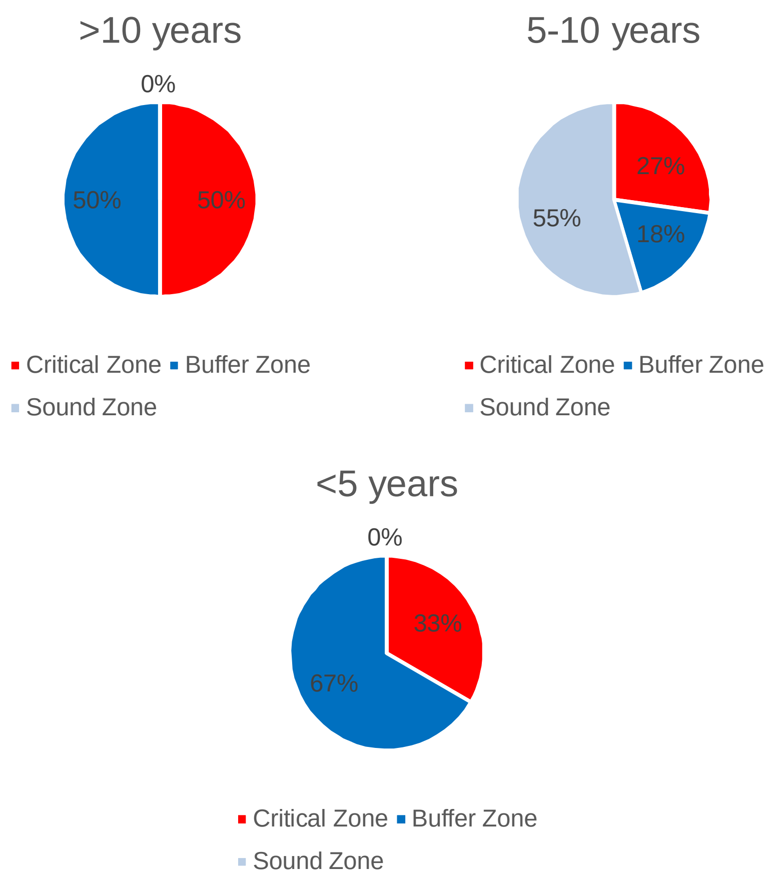

Figure 77: Analysis of Findings on VET Analysis Categorised by Age

6.4.5 VET Analysis Categorised Based on Texture Depth

The influence of texture depths is reviewed in Figure 78. The samples were characterised based on:

1. Texture depths ≤ 1.5 mm
2. Texture depths > 1.5 mm

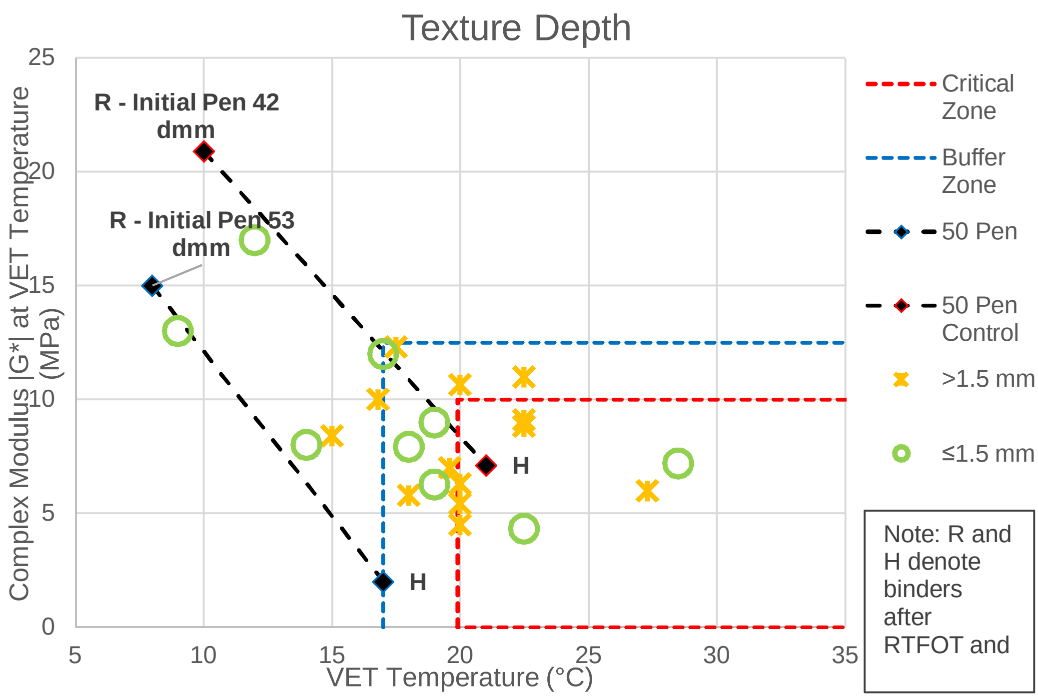

Figure 78: VET Analysis Categorised Based on Texture Depth

Figure 78 and Figure 79 shows that 46% of points having >1.5 mm texture is in the “Critical Zone”. 22% of points is having <1.5 mm texture is in the 'Critical Zone'.

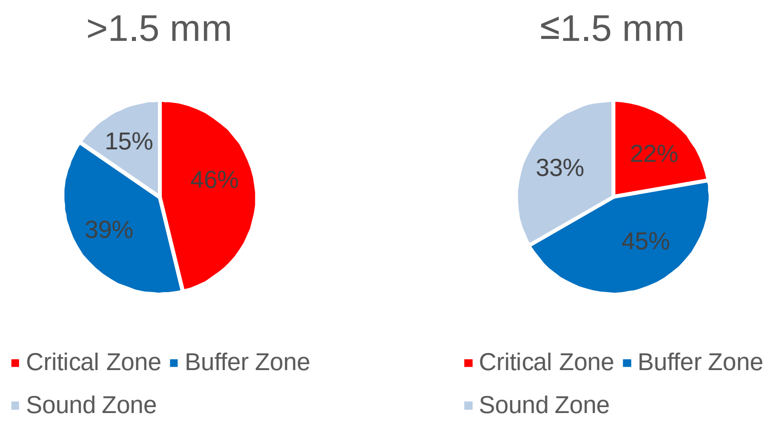

Figure 79: Analysis of Findings on VET Analysis Categorised by Texture Depth

6.4.6 VET Analysis Based on Season Laid

Figure 80 shows that the season laid plays a significant role in accelerating surface deterioration of the materials. Figure 81 shows that the materials laid in Winter are in the "Critical Zone" or the "Buffer Zone". In comparison, only 27% of points (relative minority) Not laid in Winter are in the "Critical Zone".

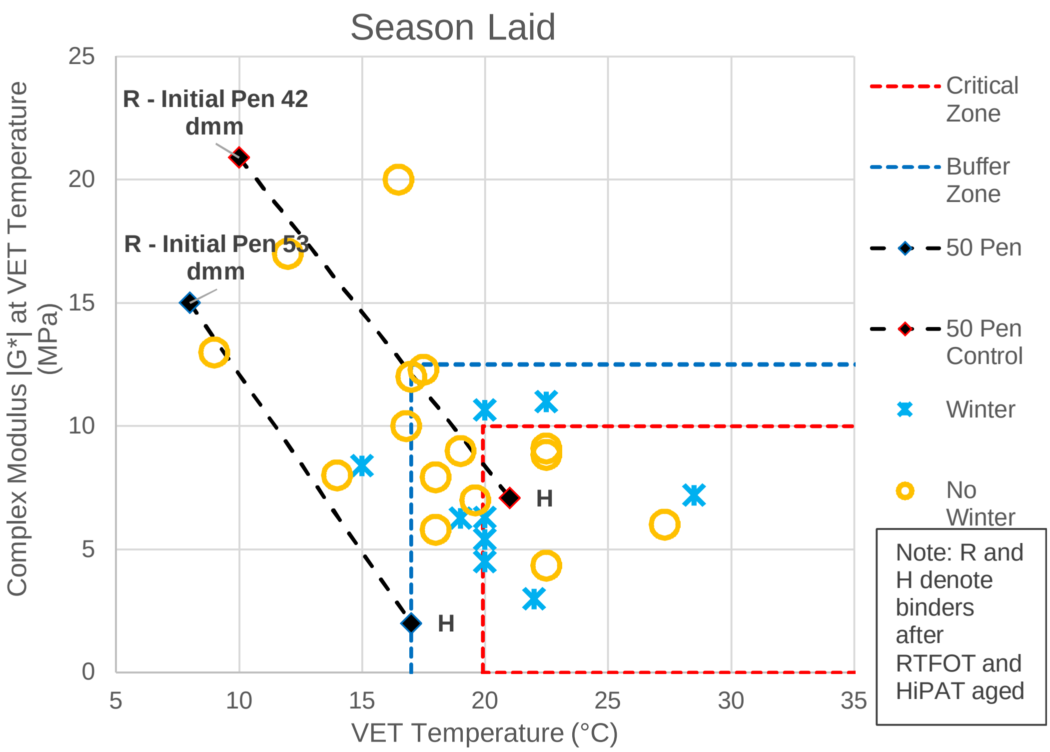

Figure 80: VET Analysis Based on Season Laid

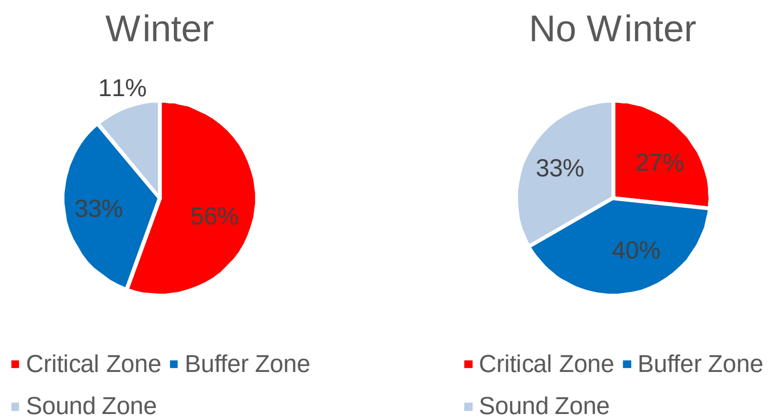

Figure 81: Analysis of Findings on VET Analysis Categorised by Season Laid

6.5 Summary

This chapter has presented findings following a detailed review and analysis of HE SRN condition data for TSCS and provided discussions on HE current value management procedures. A key element of this chapter focused on investigating the HAPMS data of 30 sites selected from the North East, East, South East and South West of England. The regions selected comprised of Areas 1, 4, 6, 8, 14 of HE SRN.

The key findings from this analysis showed that mixtures are susceptible to fretting if the air void content is high. High air void contents potentially also increase the permeability of the layer to air and water which makes the asphalt prone to stripping adversely impacting on the overall performance and durability of the TSCS. Although it is possible that surface chip loss due to fretting may lead to a high texture depth, rather than high texture leading to fretting.

The chapter also provided findings showing that higher texture depths are attributed to higher levels of fretting for TSCS. The chapter provided evidence showing low penetration values could result in increased fretting of TSCS.
The importance of laying season on the performance of TSCS was detailed. The chapter showed that TSCS laid in the winter had an increased chance of fretting in comparison to TSCS laid outside of this season.

The VET analysis detailed in this chapter was found to be able to distinguish between good and poor performing sites. The VET parameters and zones used in this research study correspond to the observed surface defects and/or material loss (fretting) on HE network. The VET analysis discussed in this chapter provides a viable model as part of pavement asset management tools to evaluate and investigate surface deterioration for TSCS.

The VET analysis shows that increased distress levels in the pavement corresponded to an increase in the T_{VET} and a decrease in the G^*_{VET}. Any increase in T_{VET} and reduction in G^*_{VET} values have been attributed to poor site conditions where surface cracks or material losses have been observed. Therefore, T_{VET} (good sites) < T_{VET} (poor sites) and G^*_{VET} (good sites) > G^*_{VET} (poor sites).

The T_{VET} is also related to the bitumen grade, production method and/or age-hardening condition. Harder grade or more age-hardened bitumen results in higher T_{VET} and lower G^*_{VET} in comparison to softer grade or less aged bitumen. Lower T_{VET} and higher G^*_{VET} indicate increased resistance to cracking and reduced ageing in the materials examined. The VET analysis was able to differentiate between sites with “Major Fretting”, “Minor Fretting” and “No Fretting”. Findings show that sites that were severely aged (penetration values ≤ 13 dmm) were fretted with evidence of surface cracks. The VET analysis discussed in this chapter can be used as a tool to monitor the condition of surface course materials on the network. The VET analysis can help select sites that should be programmed for maintenance. This can facilitate necessary actions, closer monitoring or preventative maintenance and asset management.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The aim of the work described in this thesis was to increase the understanding of, as well as investigate and assess the performance of Thin Surface Course Systems (TSCS) used on Highways England (HE) Strategic Road Network (SRN). This would improve the management of maintenance strategies for the HE SRN

To achieve this, an extensive and comprehensive literature review, from a global perspective, on the use of TSCS was carried out. This review focused on investigating main distresses and failure modes of TSCS and main factors affecting them. The main findings are summarised below:

- Fretting was acknowledged to be the main type of defect for TSCS. The key factors causing/accelerating fretting on TSCS include high air voids, inappropriate aggregate grading, lack of sufficient binder, poor adhesion between the binder and the aggregate, bitumen ageing and aggressive scuffing by the traffic, effect of climatic conditions, among others. These causes are often interdependent.

- Most of these factors are associated with material design, quality of installation and environmental aspects such as the season of installation. This research reviewed design, specification, installation, maintenance and asset management strategies of TSCS in the UK and overseas.

- The air voids' content design and in-situ assessment are considered key elements from most of the countries in order to improve asphalt surfacing performance and durability.

Historical Highways Agency Pavement Management System (HAPMS) database have been reviewed and analysed, and key sites on the SRN have been identified and selected to undertake further testing on cores and extracted bitumen. The extensive review of UK Highways Agency Pavement Management System (HAPMS) data and the additional results gathered from in-situ surveys, coring and laboratory testing led to the following conclusions:

- Findings from this research showed that most samples obtained from site had air void content >7%. In addition, individual measurements of up to 19% were reported and the overall average void content was 10.6%. The expected range for TSCS would normally be 4% to 7%. Mixtures with air void contents ≤7% are regarded as "dense" and therefore likely to be more durable. Mixtures with air void contents >7% are regarded as "open" and voided. The percentage of air void contents within the TSCS in England in comparison to other European countries is significantly higher.

- Most samples with relatively high air void content had evidence of major fretting while most samples with relatively low air void contents had evidence of no fretting. These results are in line with previous studies and general expectations.

- The texture depth seems to play a major role: most samples with texture depth values >1.5 mm experienced major fretting while the majority of samples with texture depth values <1.5 mm had no fretting.

- The results indicate that TSCS manufactured using 10 mm aggregate nominal size had no signs of major fretting in comparison to the use of 14 mm aggregate nominal size, which tends to produce a more open texture asphalt with higher air voids. However, smaller aggregate nominal sizes (0/10 mm and 0/6 mm) are considered unable to routinely meet the required texture depth specifications.

- Overall, there is a fair correlation between the age and the stiffness of the samples, the older TSCS being stiffer. This is attributed to the hardening of the binder as well as to the densification of the asphalt and it is in line with general expectations.

- In this regard, most sites with No Fretting or Minor Fretting have stiffness value greater than 3000 MPa. All sites with Major Fretting have a stiffness below 2500 MPa.

- No clear relationship was found between the Level of Fretting and the binder content nor the use of fibres.

- Samples with hard binders (low penetration values) tend to be more susceptible to fretting.

- Installing surfacing thicker than 40 mm might improve the resistance to ravelling, although some sites laid thinner than 40mm performed well in terms of service life and fretting.

- The level of fretting of TSCS seems not to be related to the age, as a fundamental factor. Instead, results indicated that the fretting phenomenon, possibly related to poor design and/or construction, is exhibited in the short/medium-term.

- Traffic does not appear to be a key factor - results showed little increase in fretting severity with increased traffic volume.

- The laying season plays a key role in the material resistance to fretting. Most TSCS laid in winter showed major fretting (64.5%) or minor fretting (19.4%) while 71% of the TSCS sites not installed in winter had no fretting. This finding shows the importance of this factor, especially considering that currently 54% of TSCS is installed in the winter period.

One objective of this study was to develop and propose a novel method, based on the Viscous to Elastic Transition (VET) parameters (gathered from rheological characterisation of binders), to assist evaluating performance and predict deterioration of TSCS. This enables exploring and identifying possible correlations between the VET parameters (T_{VET} and G_{VET}) and several asphalt/binder conditions/parameters.

Higher T_{VET} and lower G_{VET} correspond to a more critical condition (aging-hardening) of the binder. From the review of literature and further investigation, three zones on the VET plot have been identified and proposed: “Critical”, “Buffer” and “As Expected/Sound”. The main findings from this analysis are summarised as follows:

- The VET analysis (with the proposed zones) was able to identify the fretting severity: 83% of samples with major fretting located in the critical zone; sample with minor fretting located mostly in the buffer zone and majority of samples with no fretting located in the sound zone. The VET analysis was able to differentiate between sites with “Major Fretting”, “Minor Fretting” and “No Fretting”. In other words, this analysis was able to distinguish between performance of sites.

- The analysis correlated well also with the penetration ranges proposed: samples having Pen <13 dmm located mostly (75%) in the critical zone. In addition, the majority of samples older than than 10 years were either in the critical or buffer zone. In details, harder grade or more age-hardened bitumen results in higher T_{VET} and lower G^*_{VET} in comparison to softer grade or less aged bitumen. These findings are in line with general expectations.

- Reasonable correlations were found also with air voids and texture: samples with air voids <6% located mostly in the sound zone; while most of the samples with texture >1.5 mm was either in the critical or buffer zone.

- This analysis correlated well with the season of installation – most of the samples laid in winter being outside the sound zone.

In summary, this innovative analysis found that the T_{VET} is dependent on the bitumen grade, production method and/or age-hardening condition. The VET analysis showed that T_{VET} (good sites) < T_{VET} (poor sites) and G^*_{VET} (good sites) > G^*_{VET} (poor sites). In other words, increased distress levels in the pavement corresponded to an increase in the T_{VET} and a decrease in the G^*_{VET}..Therefore, the VET analysis discussed in this research could be used as a tool to monitor the current performance of surface course materials on the network. This can facilitate necessary actions, closer monitoring or preventative maintenance and asset management.

HD 30 currently does not include any binder rheology requirements even though the document acknowledges that binder oxidisation and ageing is one of the main reasons for pavement deterioration. This analysis seems to provide a viable model as part of pavement asset management tools to evaluate and investigate surface deterioration for TSCS.

7.2 Recommendations

This section summarises the key recommendations following this research. It is recommended that there should be a requirement for design and in-situ air void content within the MCHW for TSCS. Based on the findings of this research study, it is therefore proposed to incorporate the following updates to HD 30. This will help HE to understand the TSCS life expectancy performance within the network so that HE could move away from only 10 year cyclic TSCS replacement and develop a more intelligent Asset Management approach based on the in-situ performance of TSCS rather than age only.

- The assessment of binder rheology should be included as part of the scheme level survey to ascertain pavement conditions.
- Asphalt cores should be taken from locations representative of the site conditions.
- The recovered binder should subsequently be subjected to rheological testing to BS EN 14770 by applying the following test conditions:
    - The test frequencies should include 0.4 Hz and 1.59 Hz;
    - The test temperatures should cover the minimum range from 0ºC to 60ºC;
    - The temperature and complex modulus at which the phase angle value equals to 45 degrees (T_{VET} and G^*_{VET} respectively) when tested at frequency of 0.4 Hz must be reported.

Plots of Viscous to Elastic Transition (VET) temperatures, T_{VET}, against their respective complex stiffness modulus, G^*_{VET}, provide a useful tool for establishing how values in the properties of bituminous materials may be associated with different levels of age hardening and/or distress levels (cracked or uncracked sites). The recommended plot and interpretation of the zones used in the VET analysis are detailed in Figure 82 and Table 43.

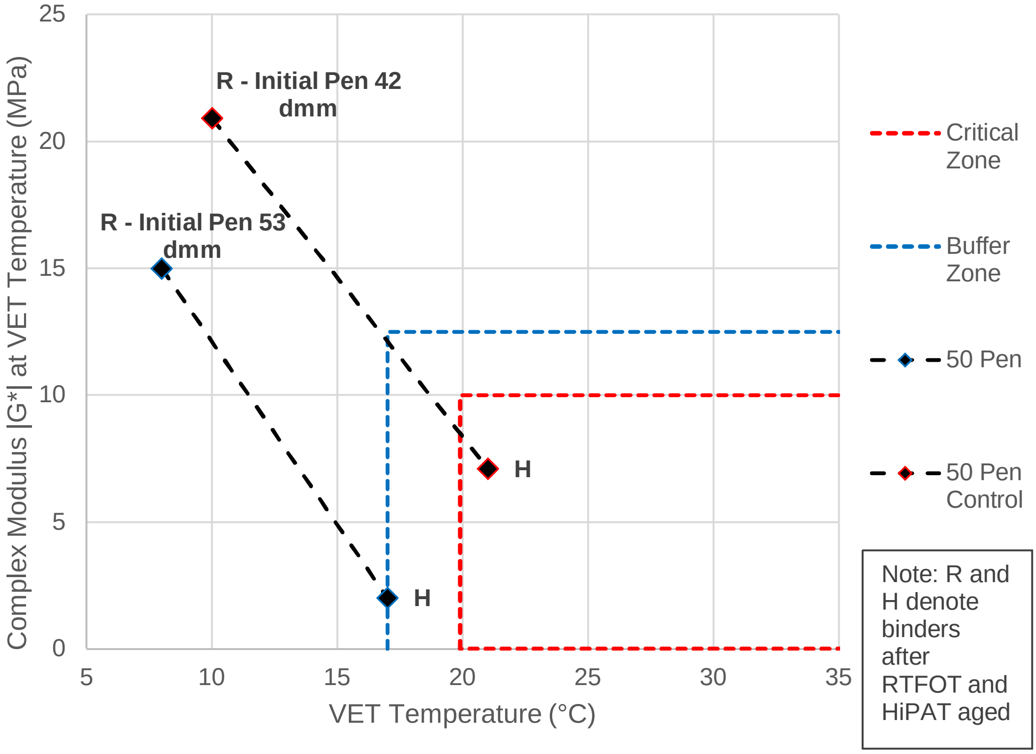

Figure 82: Plots for VET Analysis

Table 43: Interpretation of the Zones Used in the VET Analysis

Zone	T_{VET}	G^*_{VET}	Surface Condition
Critical Zone	Greater than 20ºC and	Lower than 10 MPa	Severely age-hardened material with high risk for fretting.
Buffer Zone	Greater than 17ºC and	Lower than 12.5 MPa (excluding the Critical Zone)	Age-hardened material with increasing risk for fretting.
As Expected/ Sound Zone	Lower than 17ºC	Greater than 12.5 MPa	Generally sound material with low risk for fretting.

7.3 Future Work

Areas of future work and research are detailed below:

- It is recommended that a review of HE HAPMS database is carried out periodically to ascertain current condition of TSCS on the SRN. Further to this, similar studies to ascertain influence of key parameters including the influence of air void content, stiffness, ageing, age, laying season texture depth as presented in this study should be conducted. The VET analysis developed in this study focuses on paving grade bitumen. As detailed in Figure 46, PMBs make up 17% of the SRN. Further studies and research focused on further developing the VET analysis for PMBs is recommended for future work. This is an important aspect to have a comprehensive maintenance strategy for TSCS on the SRN.

- It is important to note that although the air void content and binder properties of TSCS are clearly very important factors affecting durability of TSCS, there are also factors such as weather conditions, aggregate size, number and quality of construction joints, lack of compaction, drainage and level of supervision that will impact on the performance of the thin surface course and will need to be considered in order to successfully produce a durable TSCS. These factors are areas that must be studied in an in-depth manner to produce long lasting durable TSCS for use on the SRN.

REFERENCES

AASHTO, 2016. Standard Specification for Performance-Graded Asphalt Binder. M 320

ADEPT and MPA., 2015, Service life of asphalt materials for asset management purposes, ADEPT and MPA, 2015.

Ahmad, N., 2011, Asphalt mixture moisture sensitivity evaluation using surface energy parameters, PhD Thesis, NTEC, The University of Nottingham, UK.

Airey, G.D., 2004, Styrene butadiene styrene polymer modification of road bitumen. *Journal of Materials Science*, *39* (3), pp.951-959.

Alabaster, D., Forrest, J., Waters, J. and Herrington, P., 2015, August. Development of a High-Performance Low Noise Asphalt Surface. In *Conference on Asphalt Pavements for Southern Africa (CAPSA15), 11th, 2015, Sun City, South Africa*.

Anderson, D.A., Christensen, D.W., Bahia, H.U., Dongre, R., Sharma, M.G., Antle, C.E. and Button, J., 1994. Binder characterization and evaluation, Volume 3: Physical characterization. *Strategic Highway Research Program, National Research Council, Report No. SHRP-A-369*.

Anochie-Boateng J.K., O'Connel, J., Verhaeghe, B. and Myburgh P., 2015, Development of a New Asphalt Mix Design Manual for South Africa, Conference: 11th Conference on Asphalt Pavements for southern Africa (CAPSA 2015), Sun City, South Africa.

Apeagyei, A.K., Buttlar, W.G. and Dempsey, B.J., The Board of Trustees of The University of Illinois, 2017. *Antioxidant Treatment of Asphalt Binders*. U.S. Patent 9,605,104.

ASTM - American Society of Testing and Materials –. ASTM D4402: Standard Test Methods for Viscosity Determinations of Unfilled Asphalts Using the Brookfield Thermosel Apparatus.

Atkins., 2013, Optimum Interventions for Thin Surfacing Maintenance, HA/DfT T-TEAR Task 22 Final Report, Atkins.

Atkins., 2015, *Review of European Developments in Thin Surface Course Materials*. Highways England T-TEAR Task 430. London: Atkins.

Atkins, 2017, Task 067 Development of a Revised Prioritisation Process Value Management Light Guidance

BBA., 2013, Interim Guideline Document for the Assessment and Certification of Thin Surfacing Systems for Highways, British Board of Agreement (BBA) Highway Authorities Product Approval Scheme (HAPAS) SG3.

British Standards BS 598-102:2003, Sampling and examination of bituminous mixtures for roads and other paved areas. Analytical test methods.

British Standards BS 7941-2:2000, Methods for measuring the skid resistance of pavement surfaces - Test method for measurement of surface skid resistance using the GripTester braked wheel fixed slip device.

British Standards BS EN 933-1:2012, Tests for geometrical properties of aggregates - Determination of particle size distribution - Sieving method.

British Standards BS EN 933-3:2012, Tests for geometrical properties of aggregates - Determination of particle shape - Flakiness index.

British Standards BS EN 933-5:1998, Tests for geometrical properties of aggregates - Determination of percentage of crushed and broken surfaces in coarse aggregate particles.

British Standards BS EN 1426:2007, Bitumen and Bituminous Binders – Determination of Needle Penetration.

British Standards BS EN 1427:2007, Bitumen and Bituminous Binders – Determination of the Softening Point – Ring and Ball Method.

British Standards, BS EN 12591:2009, Bitumen and bituminous binders. Specifications for Paving Grade Bitumen.

British Standards BS EN 12607-1:2014, Bitumen and Bituminous Binders - Determination of Resistance to Hardening under the Influence of Heat and Air – Part 1 RTFOT method.

British Standards BS EN 12697-1:2012, Bituminous mixtures. Test methods for hot mix asphalt. Soluble binder content.

British Standards BS EN 12697-2:2015, Bituminous mixtures. Test methods. Determination of particle size distribution.

British Standards BS EN 12697-3:2005, Bituminous mixtures. Test methods for hot mix asphalt. Bitumen recovery. Rotary evaporator.

British Standards BS EN 12697-5:2009, Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 5: Determination of Maximum Density.

British Standards BS EN 12697-6:2003, Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 6: Determination of Bulk Density of Bituminous Specimen.

British Standards BS EN 12697-8:2018, Bituminous mixtures - Test methods for hot mix asphalt. Determination of void characteristics of bituminous specimens.

British Standards BS EN 12697-12:2018, Bituminous mixtures - Test methods for hot mix asphalt - Determination of the water sensitivity of bituminous specimens.

British Standards BS EN 12697-22:2003, Bituminous mixtures - Test methods for hot mix asphalt - Wheel tracking.

British Standards BS EN 12697-23:2017, Bituminous mixtures. Test methods. Determination of the indirect tensile strength of bituminous specimens.

British Standards BS EN 12697-26:2012, Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 26: Stiffness.

British Standards BS EN 13036-1:2010, Road and airfield surface characteristics - Test methods - Measurement of pavement surface macrotexture depth using a volumetric patch technique.

British Standards BS EN 13036-4:2011, Road and airfield surface characteristics -Test methods - Method for measurement of slip/skid resistance of a surface: The pendulum test.

British Standards BS EN 13108-1:2016, Bituminous mixtures - Material specifications - Asphalt Concrete.

British Standards BS EN 13108-2:2016, Bituminous mixtures - Material specifications - Asphalt Concrete for Very Thin Layers (BBTM).

British Standards BS EN 13108-3:2016, Bituminous mixtures - Material specifications - Soft Asphalt.

British Standards BS EN 13108-4:2016, Bituminous mixtures - Material specifications - Hot Rolled Asphalt.

British Standards BS EN 13108-5:2016, Bituminous mixtures - Material specifications - Stone Mastic Asphalt.

British Standards BS EN 13108-6:2016, Bituminous mixtures - Material specifications - Mastic Asphalt.

British Standards BS EN 13108-7:2016, Bituminous mixtures - Material specifications - Porous Asphalt.

British Standards BS EN 13108-9:2016, Bituminous mixtures - Material specifications – Asphalt for Ultra-Thin Layer (AUTL).

British Standards BS EN 13108-20:2016, Bituminous mixtures - Material specifications – Type Testing.

British Standards BS EN 13108-21:2016, Bituminous mixtures - Material specifications – Factory Production Control.

British Standards BS EN 13302:2010, Bitumen and Bituminous Binders – Determination of Dynamic Viscosity of Bituminous Binder Using a Rotating Spindle Apparatus.

British Standards BS EN 14023:2010, Bitumen and bituminous binders. Specification framework for Polymer Modified Bitumen.

British Standards BS EN 14769:2012, Bitumen and Bituminous Binders - Accelerated Long-Term Ageing Conditioning by a Pressure Ageing Vessel (PAV).

British Standards BS EN 14770:2012, Bitumen and Bituminous Binders – Determination of Complex Shear Modulus and Phase Angle – Dynamic Shear Rheometer (DSR).

British Standards BS EN 15323:2007, Bitumen and Bituminous Binders - Accelerated Long-Term Ageing/Conditioning by the Rotating Cylinder Method (RCAT).

British Standards BS ISO 11819-1:2001, Acoustics - Measurement of the influence of road surfaces on traffic Noise - Part, 1.

British Standards BS ISO 13472-2:2017, Acoustics - Measurement of sound absorption properties of road surfaces in situ - Spot method for reflective surfaces.

British Standards BS EN ISO 25178-2:2012, Geometrical product specifications (GPS) — Surface texture: Areal Part 2: Terms, definitions and surface texture parameters (ISO 25178-2:2012).

British Standards BS EN ISO 25178-2:2012, Geometrical product specifications (GPS) — Surface texture: Areal Part 2: Terms, definitions and surface texture parameters (ISO 25178-2:2012).

Capita Symonds., 2007. Report on the performance of Thin Surface Course Systems in Cumbria.

Christensen, D.W. and Anderson, D.A., 1992, Interpretation of dynamic mechanical test data for paving grade asphalt cement (with discussion). *Journal of the Association of Asphalt Paving Technologists*, *61*.

Christensen, D.W., Anderson, D.A. and Rowe, G.M., 2017, Relaxation spectra of asphalt binders and the Christensen–Anderson rheological model. *Road Materials and Pavement Design*, *18*(sup1), pp.382-403.

Daines, ME., 1986, Pervious macadam: Trials on trunk road A38 Burton bypass, Research Report 57. TRL Limited, Worthington.

DFT., 2006, Best Practice Guidelines for Specification of Modern Negative Texture Surfaces (NTS)
on Local Authority Highways, Department for Transport and UK Roads Board.

DFT., 2018, *Technical Note: Road Condition and Maintenance Data*. [Online] London: Department for Transport. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674584/road-conditions-technote.pdf [Accessed 16 Jan. 2019].

Elliott, R.C., Fergusson, C., Richardson, J., Stevenson, A. and D. James., 2013, Field Trials of a Long-Life Surfacing Material, Asphalt Professional, Issue 57, in preparation, September 2013.

Elliott, R.C., Widyatmoko, I., Chandler, J., Badr, A. and W.G. Lloyd., 2008. Laboratory and pilot scale assessment of long life surfacing for high-traffic roads. Paper 300-005 in Proceedings of the 4th Eurasphalt & Eurobitume Congress, 21–23 May 2008, Copenhagen.

Francken, L., 1998. *Bituminous Binders and Mixes*. CRC Press.

HD 37/99, 1999, Bituminous Surfacing Materials and Techniques, DMRB Volume 7.

Highways Agency, Transport Scotland, Transport Wales and The Department for Regional Development Northern Ireland, 2008, Design
Highways Agency, 2014, Investigation of Durability factors for Thin Surface Course Systems. September 2014.

Highways England., 2011. IAN157/11, 2011, Thin Surface Course Systems – Installation and Maintenance", Interim Advice Note IAN157/11, Highways Agency.

Highways England., 2018, – (a) Manual of Contract Documents for Highway Works. Volume 1: Specification for Highway Works (MCHW 1). 900 Series. Clause 942 Thin Surface Course Systems. The Stationery Office. London.

Highways England., 2018, – (b) Manual of Contract Documents for Highway Works. Volume 2: Notes for Guidance on the Specification for Highway Works (MCHW 2). 900 Series. Clause NG942 Thin Surface Course Systems. The Stationery Office. London.

Hjelle, H.M., 2007. A model for estimating road wear on in-service roads. *International Journal of Pavement Engineering*, *8*(3), pp.237-244.

IAN 154, 2012, - Revision of SHW Clause 903, Clause 921 and Clause 942 (IAN 154/12)

IAN 157, 2011, - Thin Surface Course Systems – Installation and Maintenance (IAN157/11)

Jones, C and Carswell, I., 2012, Optimisation of Modern Asphalt Surfacings TRL Report: CPR 1493. Berkshire, England.

Khojinian, A., Parry, T. and Thom, N., 2016, Strategy Management and Maintenance for Thin Surface Course Systems. In: *6th Eurasphalt & Eurobitume Congress*. Prague: 6th Eurasphalt & Eurobitume Congress.

King, G., Rowe, G. and Reinke, G., 2013, Newark Airport Runway: A Forensic Study Revisited. *Transportation Research Record: Journal of the Transportation Research Board*, (2372), pp.9-16.

KPMG, 2017, *Review of Highways England's Maintenance and Renewals Delivery*. [online] KPMG. Available at: http://orr.gov.uk/__data/assets/pdf_file/0015/25170/kpmg-review-of-highways-england-maintenance-and-renewals-delivery-march-2017.pdf [Accessed 16 Jan. 2019].

Loizos, A., 2009. *Advanced testing and characterization of bituminous materials: proceedings of the 7th international RILEM symposium ATCBM09 on advanced testing and characterization of bituminous materials, Rhodes, Greece, 27-29 May 2009*. CRC.

Manual for Roads and Bridges, Volume 7 Pavement design and maintenance, Section 3 Pavement maintenance assessment, Part 3 HD 29/08 Maintenance Assessment Procedure. London: The Stationery Office.

Manual of Contract Documents for Highway Works MCHW Clause 956, 2018, Determination of the Complex Shear (Stiffness) Modulus and Phase Angle (δ) of Bituminous Binders Using a Dynamic Shear Rheometer (DSR). Volumes I & II, "Specification for Highway Works", Highways England.

Marasteanu, M.O. and Anderson, D.A., 1999, May. Improved model for bitumen rheological characterization. In *Eurobitume workshop on performance related properties for bituminous binders*. Brussels, Belgium: European Bitumen Association.

McHale, M.J., Carswell, I. and Roe, P., 2011, *New surface course specification for Scotland* (No. TRL Report 670).

Migliori, F, Ramond, G, Ballie, M, Brule, B, Exmelin, C, Lombardi, B, Samanos, J, Maia, AF, Such, C, and Watkins, S, 1999, Correlations between the thermal stress cracking of bituminous mixes and their binders' rheological characteristics, Eurobitume Workshop on Performance Related Properties for Bituminous Binders", Luxemburg, 3-6 May 1999.

Minitab Inc. (2010). Statistical Inference and t-Tests. *Minitab Inc*.

Morgan, P.A., Stait, R.E., Reeves, S. and Clifton, M., 2010. The feasibility of using twin-layer porous asphalt surfaces on England's strategic road network. *TRL Published Project Report*.

Neal N., 2014, Identifying the Intervention Point for Preventative Maintenance of TSCS with Surface Dressing in Lincolnshire, C Neal, Proc. 13th Annual International Conference on Asphalt, Pavement Engineering and Infrastructure, Liverpool John Moores University, 2014.

Neal, N., 2015, Identifying the Intervention Point for Preventative Maintenance of Thin Surface Course Systems with Surface Dressing in Lincolnshire. Lincs Laboratory.

Nicholls, J C., 2002, A history of the recent thin surfacing revolution in the United Kingdom. TRL Report TRL522. Crowthorne: Transport Research Laboratory.

Nicholls, J C, I Carswell and P C Langdale., 2002, Durability of thin asphalt surfacing systems – Part 1, Initial findings. TRL Report TRL557. Crowthorne: Transport Research Laboratory.

Nicholls, J C, and I Carswell., 2004, Durability of thin asphalt surfacing systems – Part 2, Findings after three years. TRL Report TRL606. Crowthorne: Transport Research Laboratory.

Nicholls, J C, I Carswell, C Thomas and L K Walter., 2007, Durability of thin asphalt surfacing systems – Part 3, Findings after six years monitoring. TRL Report TRL660. Crowthorne: Transport Research Laboratory.

Nicholls, J C, M J McHale and R D Griffiths., 2008, Best practice guide for the durability of asphalt pavements. TRL Road Note RN 42. Crowthorne: Transport Research Laboratory.

Nicholls, J C, I Carswell, C Thomas and L K Walter., 2009, Durability of thin asphalt surfacing systems – Part 4, final report after nine years monitoring. TRL Report TRL674. Crowthorne: Transport Research Laboratory

Nicholls, C., 2017, *Asphalt Mixture Specification and Testing*. CRC Press.

NRA., 2015, Manual of Contract Documents for Roadworks. Volume 1 - NRA Specification for Road Works. Series 900 - Road Pavements - Bituminous Bound Materials, National Roads
Authority, Dublin, 2015.

Nunn, M., 1994, Evaluation of Stone Mastic Asphalt (SMA): A High Stability Wearing Course Material. *TRL Project Report*, (PR 65).

Nunn, M., 2004, Development of a more versatile approach to flexible and flexible composite pavement design TRL 615.

OECD, Economic Evaluation of Long-Life Pavements. Paris: OECD Transport Research Centre, 2005. ISBN 92-64-00856-X

OECD, Long-life surfaces for Busy Roads. Paris: OECD International Transport Forum, 2008. ISBN 978-92

Ojum, C., Widyatmoko, I. and Edwards, P., 2017, Task 409: Collaborative Research into the Next Generation of Asphalt Surfacings. [online] AECOM. Available at: https://www.aecom.com/uk/wpcontent/uploads/2017/09/report_highways-england_task-409_subtask-1.pdf [Accessed 14 Jan. 2019].

Ojum, C., Tuck, J. and Widyatmoko, I., 2017, Task 1-111 Sub-Task 1: Project Report on Premium Asphalt Surfacing System (PASS) Road Trial. [Online] AECOM. Available at: https://www.aecom.com/uk/wp-content/uploads/2018/03/report_highways-england_task-1-111_subtask-1.pdf [Accessed 14 Jan. 2019].

Olard, F., 2012, GB5 Mix Design: High-Performance and Cost-Effective Asphalt Concretes by Use of Gap-Graded Curves and SBS Modified Bitumen, Road Materials and Pavement Design Volume 13, Supplement 1, 2012 Special Issue: Papers from the 87th Association of Asphalt Paving Technologists' Annual Meeting, April 1-4, 2012.

ORR., 2018, *Annual Assessment of Highways England's Performance (2017 - 2018)*. [online] Office of Rail and Road. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/725623/annual-assessment-of-highways-englands-performance-2018-web.pdf [Accessed 16 Jan. 2019].

Read, J. and Whiteoak, D., 2003, Shell Bitumen Handbook, 5th Ed, Shell Bitumen UK. Thomas Telford

Roads Agency, 2013, An Initiative of The South African National Roads Agency Ltd

Rowe, G.M., 2014, Interrelationships in rheology for asphalt binder specifications. In *Proceedings of the Fifty-Ninth Annual Conference of the Canadian Technical Asphalt Association (CTAA): Winnipeg, Manitoba*.

Rowe, G.M., King, G. and Anderson, M., 2014, The influence of binder rheology on the cracking of asphalt mixes in airport and highway projects. *Journal of Testing and Evaluation*, *42*(5), pp.1-10.

Said, S., 2005, Ageing effect on mechanical characteristics of bituminous mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, (1901), pp.1-9.

Sandberg, U., Kragh, J., Goubert, L., Bendtsen, H., Bergiers, A., Biligiri, K.P., Karlsson, R., Nielsen, E., Olesen, E. and Vansteenkiste, S., 2011, Optimization of thin asphalt layers: state-of-the-art review.

SETRA., 2008, Technical guide: The use of standards for hot mixes. Available at: https://www.cerema.fr/system/files/documents/2018/04/US_0840A-The_use_of_standards_for_hot_mixes.pdf

South African National Standard SANS 3001-PD1:2015, Edition 1: Determination of permanent deformation and moisture sensitivity in asphalt mixes using a one-third-scale model mobile load simulator (MMLS3) - Draft-July-2014

SHRP, 1994, Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program.

Smith A. and Visser A.T., 2008, A South African Road Network Classification based on traffic loading, Proceedings 8th International

Symposium on Heavy Vehicle Weights and Dimensions, Johannesburg, South Africa.

Statistics Solutions. (2013). What is Linear Regression [online]. Available at: https://www.statisticssolutions.com/what-is-linear-regression/ Document. [Accessed on 28 March 2020]

Thom N., 2014, Pothole Formation: Experiments and Theory, Asphalt Professional No. 60, April.

Transport Scotland., 2015, Transport Scotland Interim Amendment 35/15: TS2010 Surface Course Specification and Guidance.

Viner, H., Abbott, P., Dunford, A., Dhillon, N., Parsley, L. and Read, C., 2006, Surface texture measurement on local roads. *Published Project Report PPR148, TRL Limited, August*.

Voskuilen, J.L.M. and Verhoef, P.N.W., 2003, Causes of premature ravelling failure in porous asphalt. In *Sixth international RILEM symposium on performance testing and evaluation of bituminous materials* (pp. 191-197).

Watson D.E., 2003, An Updated Review of SMA and Superpave Projects. National Centre for Asphalt Technology (NCAT).

Widyatmoko, I., Elliott, R.C., Heslop, M.W. and Williams, J.T., 2002, Ageing Characteristics of Low Penetration Bitumen. In *Proceedings of the Fourth European Symposium on performance and durability of bituminous materials & hydraulic stabilised composites*.

Widyatmoko, I., Elliott, R.C. and Heslop, M.W., 2004, Mapping crack susceptibility of bituminous materials with binder durability. In C. Petit, I.L. Al-Qadi and A. Millien eds., *Fifth International RILEM Conference* *on Reflective Cracking in Pavements* (pp. 367-374). RILEM Publications SARL.

Widyatmoko, I., Heslop, M.W. and Elliott, R.C., 2005, Viscous to Elastic Transition Temperature of Bitumen and the In-Situ Performance of Bituminous and Asphaltic Materials. *Asphalt Professional No. 14* (ISSN 1479-6341)

Willway, T., Baldachin, L., Reeves, S., Harding, M., McHale, M. and Nunn, M., 2008, The effects of climate change on highway pavements and how to minimise them: Technical report. *The Effects of Climate Change on Highway Pavements and how to Minimise them: Technical Report*, *1*(1), pp.1-111.

ZTV Asphalt-StB 2007, German Asphalt Specification, TL Asphalt-StB 2007 Additional technical terms of contract and guidelines for the construction of road surfacing from asphalt [German designation: ZTV Asphalt-StB 07] Asphalt guidelines to ensure the usable life time of hot mix asphalt pavements, www.asphalt.de.