Task 451: Developing a Simulative Laboratory Ageing Testing Method for Thin Surfacings

Final Report

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LIST OF FIGURES

LIST OF TABLES

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1 INTRODUCTION

1.1 Background

The high level objectives of Highways England are value for money, driving innovation and improving efficiency. As such, there is now greater emphasis on asphalt surfacings to deliver cost reduction as well as environmental benefits.

Thin Surface Course Systems (TSCS) are the current preferred type of surfacing on the Strategic Road Network, introduced on UK roads in the late 1990's. Previous research has shown that these materials can be very durable and last up to 16 years, even on roads with high traffic levels. However recent harsh winters have led to some road surfaces deteriorating prematurely and very rapidly.

Ageing of bituminous materials are predominantly caused by oxidation, although researchers have also acknowledged other mechanisms such as loss of volatiles, exudative hardening and physical hardening.

Like many organic substances, bitumen slowly oxidises when in contact with air. The degree of oxidation is highly dependent on the temperature, time and the thickness of the bitumen film. There is a significant view that the binder content and ageing has a significant role on the in-situ performance of road surfacings.

It is essential that a detailed laboratory study is carried out in order to understand binder oxidisation in more detail as this is expected to have a direct effect on the in-situ performance of the TSCS. Short term binder ageing test methods such as Thin Film Oven Test (TFOT) and Rolling Thin Film Oven Test (RTFOT) exist, however research carried out previously concluded that the interaction between binder and aggregate has a major influence on ageing characteristics. Therefore just ageing the binder on its own is not an adequate means of predicting long-term performance. Consequently a new method which is capable of simulating the mechanisms of ageing in the asphalt mixture is required. The new test method should facilitate better understanding of the interaction between aggregate and bitumen, specifically in relation to the resistance to ageing and its effect to mechanical properties of the asphalt mixtures.

Highways England commissioned AECOM (formerly URS) supported by ACLAND on 28th November, 2014 to carry out a study to explore simulative laboratory ageing testing method for thin asphalt surfacing. This study was awarded under Highways England Framework for Transport Related Technical, Engineering Advice and Research – Lot 2: 4/45/12 with Package Order Reference – 451 (4/45/12) ARPS.

This study was divided into the following tasks

1. Carry out laboratory trials and testing.
2. Develop a simulative ageing test method for TSCS.

1.2 Current Practices

Thin Surface Course Systems (TSCS) are “proprietary bituminous products with suitable properties to provide a surface course that are laid at a nominal depth of less than 50 mm” (Highways Agency, 2012).

TSCS were developed in France and Germany in the late 1970s and early 1980s. Two types were developed based on asphalt concrete and stone mastic asphalt (SMA), but these were laid at different nominal thicknesses and this led to different descriptions of the installed products:

- UTLAC Ultra-thin asphalt concrete surfacing developed in France with a nominal (average design) thickness of 10 mm to 20 mm. This product is not specified in Manual of Contract Documents for Highway Works, Volume 1, (MCHW 1). A European Technical Assessment document (ETA) has been published (ETAG 035) under Mandate 387 which includes installed performance requirements (maximum defects with time) and bonding requirements. There is also a Harmonised Standard for the material used for UTLAC which is BS EN 13108-9 *Bituminous mixtures — Material specifications — Part 9: Asphalt for Ultra-Thin Layers (AUTL).*
- Very thin asphalt concrete surfacings (VTAC), generally utilise polymer modified bituminous binder and are laid to a nominal thickness of 18 mm to 25 mm. These products are specified in MCHW1 clause 942 TSCS. The asphalt may comply with BS EN 13108-1, *Bituminous mixtures — Material specifications — Part 1: Asphalt Concrete* or BS EN 13108-2, *Part 2: Asphalt Concrete for very thin layers* or BS EN 13108-5 *Part 5: Stone Mastic Asphalt.*
- SMA Stone mastic asphalt, either unmodified bitumen with fibres or with polymer modified bitumen and a nominal thickness of 25 mm to 50mm. BS EN 13108-5, *Bituminous mixtures — Material specifications — Part 5: Stone Mastic Asphalt.* SMA as a surface course is not specified in MCHW1, but can comply with clause 942 if supported by approved certificates.

The German specification for SMA provided lower macrotexture than the minimum demanded at the time in the UK. However, there have been anecdotal reports stating that some producers changed the composition to achieve an increase in macrotexture, which led to some early-life failures. Reduced binder content and associated higher air voids were thought to be the key problems.

TSCS as specified in MCHW 1 clause 942 must have a Highway Authorities Product Approval Scheme (HAPAS) or equivalent certificate.

Only TSCS that are hot mixed asphalts laid at above a nominal thickness depending on the aggregate size are permitted, see Table 1-1 and Table 1-2 taken from MCHW clause 942 TSCS:

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

Table 1-1: Design Target Layer Thickness (excluding Site Categories H1, H2, L and J)

Only thin surface course systems with an upper (*D*) aggregate size of 10mm or less are permitted on Site Categories H1, H2, L and J and these sites need to be identified in the contract specific Appendix 7/1.

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

Table 1-2: Design Target Layer Thickness for Site Categories H1, H2, L and J

The expected durability of TSCS is based on the specification of the asphalt and best practice. TSCS are expected to be laid on a properly designed road where the durability of the surface layer is not determined by bottom-up fatigue cracking. In addition, it is assumed that the mix is properly designed, well compacted and properly bonded. The durability of TSCS also depends on local conditions, local climate, mix formula, traffic conditions, characteristics of bitumen and aggregate.

Minimum binder content is specified in MCHW1 clause 942 TSCS in order to improve durability see Table 1-3. BBTM is the French term for Asphaltic Concrete (AC) laid as a very thin asphalt surfacing.

	MINIMUM TARGET DESIGN BINDER CONTENT*	
Maximum Aggregate Size (D)	Mixture types: EN13108, 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	6.8 **

This is the B_{min} value declared in CE marking and is uncorrected for aggregate density. Guidance on binder corrections for aggregate density is given in PD6691. Some aggregate types e.g. steel slag do not follow this correction process and the target binder content should be considered in light of experience of satisfactory use.

*** These mixtures are not considered appropriate for application on the Motorway and Trunk Road Network so should only be called up with very careful consideration.*

Table 1-3: Minimum Design Binder Content

Table 1-4 presents the durability of thin surfacing in years of service life for major roads, motorways and heavily trafficked roads. As can be seen the life depends on the type of the thin surfacing and increases with the nominal thickness. SMA with a greater thickness has a longer life.

Type	Thickness (Mm)	15% Lower Level (Years)	European Average (Years)	85% Higher Level (Years)
UTLAC	10 – 20	8	10	12
VTAC	18 – 25	8	10	12
SMA	25 – 50	14	20	25

Table 1-4: Durability of Thin Surfacing on Major Roads (EAPA, 2007)

Therefore, the European average life of the thin asphalt surfacing is about 10 years for nominal thickness lower than 25mm and about 20 years for nominal thickness greater then 25mm.

However, thin asphalt surfacing does not always function satisfactorily to the end of its design life. Figure 1-1 shows the age of the TSCS when they have been treated in Lincolnshire - the majority of sites were treated after 5-6 years in service (Neal, 2015).

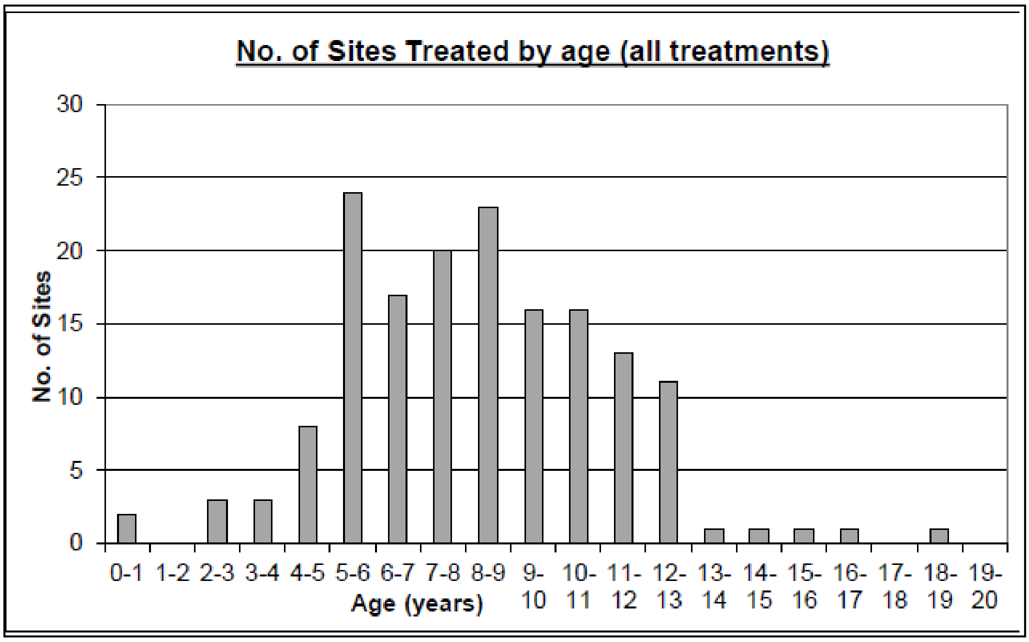


Figure 1-1: Number of Sites Treated at Different Age

2 MODES OF FAILURES

The deterioration mechanisms can be categorised into five groups of influencing factors which act on a surface. These five influencing factors do not always behave in isolation and if two or more mechanisms occur simultaneously failure in TSCS will normally be accelerated (UKRLG, 2006).

- **Internal** material based mechanisms (i.e. stability of mixture design, Binder properties Aggregate/binder affinity).
- **Traffic** loading related forces including direct loading, shear and tension loading due to braking, acceleration and turning and compression loading mainly from direct static and dynamic traffic loads.
- **Environmental** influences largely related to oxidisation and water saturation leading to the destruction of the aggregate/binder bond.
- **Substrate** strain loading. The substrates onto which TSCS are applied are often subject to vertical and horizontal movements that impose strains on any overlay or inlay systems.
- **Interface** shear stress. As the surface thickness is reduced there is an increase in the horizontal shear stress at the base of the surface layer due to lateral traffic loading.

With regard to the most common categories of defect, fretting (including loss of aggregate, mortar fretting, and stripping) and cracking were first and second whilst delamination was third (TRL Report 674). Based on the TRL report fretting, cracking, and delamination were responsible for about 61%, 35% and 4%, respectively, of the TSCS defects from 1992 to 2005. Considering the “influencing factors” above, fretting could be linked to the Internal, Traffic, and Environment factors. Cracking could be linked to the Internal, Traffic, Environment, and Substrate. Delamination could be linked to the Interface mechanism. Since fretting is the significant mode of failure in the TSCS, hence, the “Internal”, “Traffic”, and “Environment” factors must at least be considered and simulated in the proposed test.

2.1 Fretting

Fretting as the most common failure mode is the progressive loss of interstitial fines from the road surface. It normally starts to appear after one to three years other than for the 10 mm SMA systems which, based on TRL Report 674, no discernible fretting was observed until seven years.

Fretting occurs when the micromechanical bond between binder and aggregate reaches a critical point. Fretting is usually initiated by the loss of a single particle of coarse aggregate. Once a single stone is loosened, water has more ready access to the matrix of the layer; this process comprises:

- Critical horizontal loading acted on coarse aggregate particles;
- The loaded aggregate is loosened, where the bitumen/aggregate bond is inadequate, and eventually displaced.
- Once a single aggregate particle is displaced the adjacent aggregate particles and/or matrix is deprived of lateral support, progressive deterioration takes place.

The initiation of fretting is often associated with the longitudinal construction joints as shown in TRL PPR708 and reproduced in Figure 2-1. Ideally when laying TSCSs the pavers should lay in echelon, hence ensuring that the asphalt is hot on the both sides of the longitudinal construction joint prior to compaction. Unfortunately during maintenance this is generally not possible and hot material is laid against existing cold material on the side of the joint. This results in the rapid cooling of the adjacent material, reducing the compactability of the asphalt at the joint, which may make this material more susceptible to water ingress and hence fretting. TRL reviewed the performance of 55 sections of TSCS (between 4 and 8 years old) in three Highways England maintenance areas and they found that 73% of the sections were fretting at the longitudinal joint. It has been observed that maintenance plans which utilising heat to remove road marking may have contributed to fretting of TSCS adjacent to longitudinal joints.

Figure 2-1: Fretting at a Longitudinal Joint in TSCS (after TRL PPR708)

Figure 2-2 illustrates progressive fretting which took place in a short period on a stretch of road, whilst Figure 2-3 illustrates fretting which resulted in development of potholes and delamination of TSCS layer.

Figure 2-2: Fretting on the Mat

Figure 2-3: TSCS fretting and delamination (after Thom, 2014)

2.2 Cracking

As stated earlier in this report that cracking is the second most significant form of deterioration in TSCS and TRL Report 674 stated that it was responsible for about 35% of the defects from 1992 to 2005. As surface material ages it becomes hardened and brittle due to oxidisation of binder and ultimately cracks occur. For TSCS therefore, ductility and adequate binder content is required to reduce cracking potential. Cracking of the TSCS system layer will generally be a function of the substrate on which it is laid more than of the overlying TSCS.

2.3 Delamination

According to UKRLG (2006), delamination as the third most significant cause of TSCS deterioration has been found to occur more likely when TSCS is applied to a smooth substrate or where there is lack of bond with the substrate. Furthermore TRL Report 674 found that delamination was not evident on BBTM (TSCS) sites in the first 5 years and the risk increased with time, whilst SMA sites (normally laid at greater nominal thickness) showed practically no signs of delamination. This seems to suggest that thinner TSCS is more susceptible to delamination unless laid over a binder course. The 5-year guarantee in Clause 942 motivates contractors to recommend the use of binder course when there is doubt over the planned or milled substrate, somewhat negating the benefit of thin applications. A rapid on-site test to remove doubts concerning substrates is needed. Although not part of this Project a Shear Surface Strength test for substrates has been investigated under Highways England project: Task 318(4/45/12) Durability of High Friction Surfacing (report to be published at the Highways England's Knowledge Compendium in 2016).

3 THE PRINCIPAL FACTORS AFFECTING BITUMEN/AGGREGATE ADHESION

It is normally considered that approximately 80% of the factors influencing the durability of asphalt are controllable during production and construction (Read et al, 2003). Furthermore Road Note 42 stated that the asphalt durability can be maximised by the control of water (getting it away from the structure, if not actually stopping it ever entering); limiting the number of joints (both vertical and horizontal), and sealing those joints; and adequate compaction (particularly at joints). Also, TSCS laid in winter has been found to be more prone to early fretting as the surface is more likely to have been insufficiently compacted.

As mentioned in the previous Section, fretting occurs when the micromechanical bond between binder and aggregate deteriorates, commonly referred to as 'stripping', which is primarily due to the action of moisture. Main factors influencing moisture damage are summarised in Table 3-1 and Table 3-2. These tables show that the aggregate type and shape, binder content, and air voids are the main factors influencing the moisture damage and hence the fretting in asphalt pavement.

DAMAGE MECHANISMS	DESCRIPTIONS
Aggregate Shape Characteristics	Aggregate shape characteristics influence adhesion between the aggregate and the binder. Increased aggregate texture and angularity leads to increased surface area and therefore results in increased total bond energy in the mixture. For particle size distributions that are discontinuous such as SMA, the number of contact points between coarse aggregate particles is important hence producers need to control the 2mm particle size and shape. Also, the 6mm SMA has greater resistance to fretting than a variable shaped 14mm open-graded material.
Binder Film Thickness	Damage in asphalt mixtures can occur within the bitumen mastic (cohesive failure) or at the aggregate-bitumen mastic interface (adhesive failure). The thickness of the mastic around the aggregate greatly contributes as to whether cohesive or adhesive failure occurs.
Surface Energy	One of the main factors is the type of aggregate. This has a considerable influence on bitumen adhesion due to differences in the degree of affinity for bitumen. The vast majority of aggregates are classified as 'hydrophilic' (water loving) or 'oleophobic' (oil hating). Aggregates with high silicon oxide content, e.g. quartz and granite (i.e. acidic rocks) are generally more difficult to coat with bitumen than basic rocks such as basalt and limestone. The phenomenon of stripping of the bitumen in the presence of water can therefore be related to the surface charges.
Air Void Distribution and Permeability	Water permeability is an important factor influencing moisture damage. Mixtures with higher air voids are likely to be interconnected and hence water can readily access the mixture.
Surface Texture	If water is removed from the surface by interconnected voids then the pressure is reduced and so damage is less. However, when negatively textured surfaces are filled with detritus it is reported that damage occurs due to water retention. Much more so on TSCS in comparison to HRA which is much less permeable.

Table 3-1: Main Factors Influencing Moisture Damage

FAILURE MECHANISMS	DESCRIPTIONS
Pore pressure	This type of adhesivity failure mechanism is most important in open or poorly compacted mixtures where it is possible for water to be trapped as the material is compacted by traffic. Once the material becomes effectively impermeable, subsequent trafficking induces pore water pressure. This creates channels around the bitumen/aggregate interface leading to loss of adhesion.
Chemical de-bonding	Diffusion of water through a bitumen film can lead to layers of water at the aggregate surface. The salt content of bitumen can lead to osmosis which encourages diffusion which damages the bond. Ageing bitumen produces some water soluble components.
Hydraulic scouring	Hydraulic scouring or pumping occurs in the surface course and is caused by the action of vehicle tyres on a saturated pavement surface, i.e. water is forced into surface voids in front of the vehicle tyre.
Film rupture	At sharp edges on the aggregate surface where the bitumen film is thinnest, it has been shown that water can penetrate through the film to reach the surface of the aggregate.

Table 3-2: The Main Adhesivity Failure Mechanisms in Asphalt

Moisture diffusion and pore pressure development from entrapped water in the air voids (i.e. pumping action) were identified as the main physical and/or mechanical processes that ultimately can lead to pavement distresses such as fretting and cracking (Solaimanian et al, 2003).

Moisture diffusion through asphaltic materials is a long-term process that affects the durability of asphalt pavements. As moisture infiltrates into the asphalt mixture, the physico-chemical properties of the binder can change hence reducing its cohesive strength. Additionally, in the presence of moisture, the adhesive bond between aggregate and asphalt binder deteriorates and can eventually result in stripping.

In asphalt mixtures some of the pores are interconnected and allow the water to move through the pavement. Dynamic traffic loads can cause high water pressure fields within the pores that are filled with water. These high pore pressures can lead to cracking of the binder film thus facilitating the ingression of moisture to the binder/aggregate interface (Figure 3-1), and resulting in the increase of tensile stress within the material (Figure 3-2). The latter implies that traffic speed can increase the tensile stress (possibly due to increase in pumping action) and lower tensile stresses can be expected on denser asphalt mixtures with less than 5% air voids) or porous asphalts with more than 20% air voids (Thom, 2014).

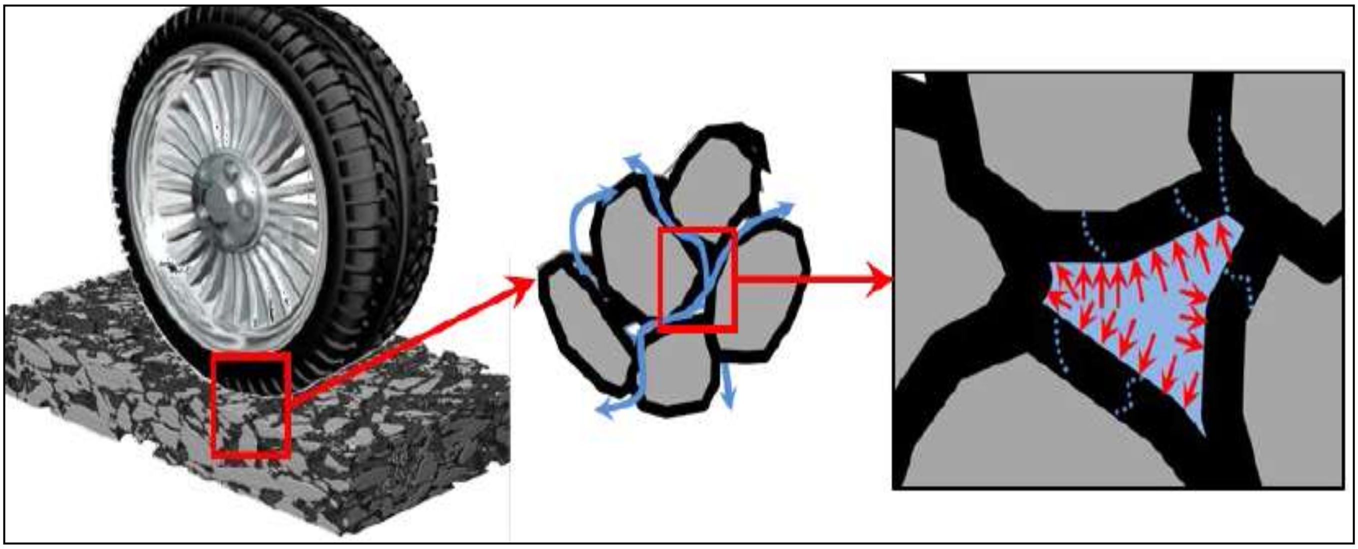


Figure 3-1: Pore pressure development due to pumping action (after Solaimanian et al., 2003)

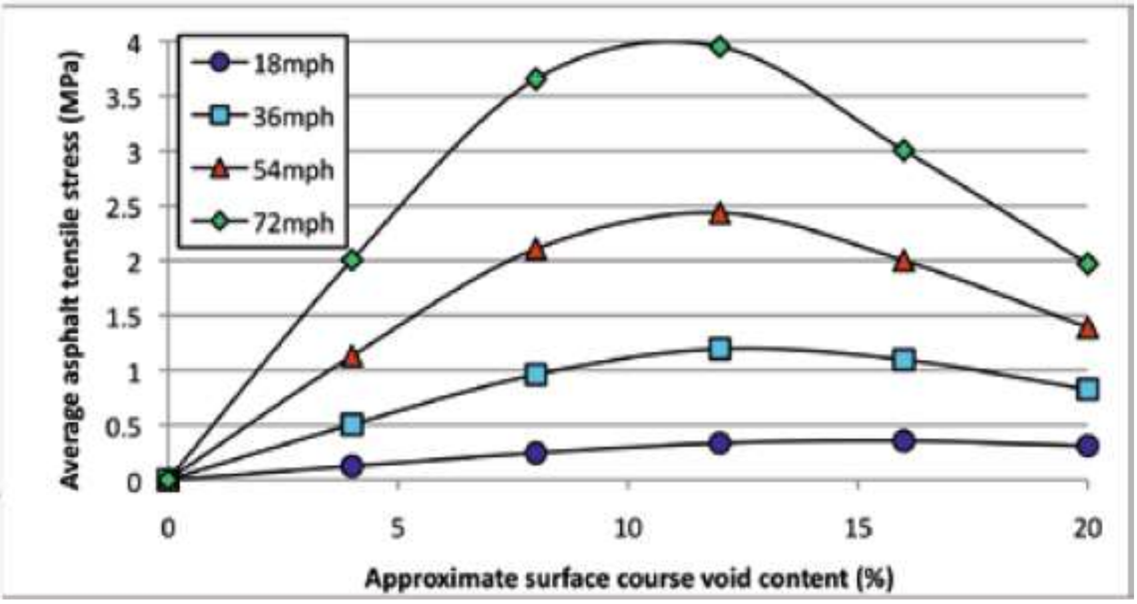


Figure 3-2: Tensile Stress as a Function of Surface Air Voids [Thom, 2014]

4 TEST METHODS

4.1 Current Test Requirements

Currently TSCS as specified in MCHW 1 clause 942 must have a Highway Authorities Product Approval Scheme (HAPAS) or equivalent certificate and must satisfactorily complete Stages 1 to 6 of the BBA Guideline (2013). The Stage 3 of the process is laboratory and field testing of TSCS; these are summarised in Table 4-1. It must be noted here that, currently, there is no performance level specified for resistance against moisture damage (water sensitivity testing).

TEST/METHOD	METHOD	PERFORMANCE LEVELS	APPLICABILITY OF TEST
Laboratory Tests			
Polished Stone Value (PSV) of the Aggregate – Aggregate Abrasion Value (AAV)	BS EN 1097-8: 2009	HD36/06	Data always required for aggregates used for installation / performance trial.
Resistance to Permanent Deformation (45°C or 60°C), WTS_{AIR} (mm•1000 Cycles)	BS EN 12697-22: 2003 Procedure B Small Device in Air	Table B.1, PD 6691	Required when the nominal laid thickness + claimed regulating depth ≥20 mm.
Torque Bond Test Shear Stress (kPa) Installation Depth (mm)	Appendix A.3	≥400 Record	Paver laid hot materials only. To be carried out between 28 and 56 days after installation.
Water Sensitivity (ITSR)	BS EN 12697-12	Record	Not applicable for CE marked asphalt products
Road Tests			
Visual Observations – Initial Visual Assessment by BBA Inspection Panel. After 2 Years Trial Period	Appendix A.10	- ≥ G	Required Required
Surface Macrotexture Depth Initial Surface Macrotexture Depth (mm)	BS EN 13036:2010	IAN 154 Sept 2012 Table 9/3	Always required
Retained Surface Macrotexture Depth (mm)		IAN 154 Sept 2012 Table NG 9/32	

Table 4-1: BBA Laboratory Tests

4.2 Moisture Sensitivity Tests

The tests developed to determine moisture susceptibility of bituminous mixtures can be divided into two general categories: those that are conducted on loose samples and those that are conducted on compacted mixes. Tests of the first category normally provide an estimate of the bitumen/aggregate compatibility and stripping potential. Tests of the second category attempt to take into account the mix properties, water action, and traffic loading. Some tests of the second group provide moisture sensitivity of the mix on the basis of combined parameters such as strength or modulus before and after conditioning or permanent deformation under loading and water actions.

4.2.1 *Moisture Sensitivity Test on Loose Samples*

Table 4-2 summarises the moisture sensitivity tests on loose samples (after Solaimanian et al, 2003).

TEST	DESCRIPTIONS
Methylene Blue Test	The methylene blue test attempts to identify the harmful clays and dust available in the fine aggregate. This test does not directly provide a measure of stripping since no bitumen is used. However, the results can be used to decide whether potential for stripping exists because if aggregates are coated with montmorillonite type clay, proper coating will not take place between the aggregate and bitumen.
Film Stripping Test (California Test 302)	This is a modified version of test procedure AASHTO T182 (Coating and Stripping of Aggregate/Bitumen Mixtures). 60g mass of aggregate coated with bitumen is placed in an oven for a certain time. The sample is then cooled and placed in a jar which rotates. The sample is removed and the percentage of stripping is estimated when the jar is viewed under fluorescent light. The results are reported in terms of the percent total aggregate surface stripped.
Static Immersion Test (AASHTO T182)	The aggregate/bitumen mixture is cured for 2 h at 60°C and cooled to room temperature. It is then placed in a glass jar and covered with 600 mL of distilled water. The jar is capped and placed in a 25°C water bath and left undisturbed for 16 to 18 h. The amount of stripping is visually estimated on the basis of the established criteria. The total visible area of the aggregate is estimated as either less than or greater than 95%. This is a major limitation of the test because the results are decided purely on the basis of a subjective estimate of less than or greater than 95%.
Dynamic Immersion Test	The dynamic immersion test is used to accelerate the stripping effect compared with the static immersion test. The test has not been standardized and is not widely used. Samples of aggregate/bitumen mixtures are prepared the same way as for the static immersion test but are subjected to 4 h of agitation.
Chemical Immersion Test	The chemical immersion test method covers the determination of the adhesion of bitumen to aggregate by means of boiling aggregate/bitumen mixtures successively in distilled water. Solutions of sodium carbonate in distilled water are prepared at different concentrations. The solution is brought to boiling and the prepared aggregate/bitumen mix is placed into the boiling water. After 1 min of boiling, the water is drained and the sample is placed on filter paper. The sample is examined for stripping after it is dry.
Surface Reaction Test	This test is based on the principle that calcareous or siliceous minerals will react with a suitable reagent and create a gas as part of the chemical reaction products. This generated gas, in a sealed container, will create a certain pressure that can be considered proportional to the mineral surface area exposed to the reagent. The reagent is typically an acid.
Texas Boiling Test	The procedure requires adding aggregate/bitumen mixture to boiling water and bringing the water back to boiling after this addition. After 10 min, the mixture is allowed to cool while the stripped bitumen is skimmed away. The water is drained, and the wet mixture is placed on a paper towel and allowed to dry. Visual rating is conducted to assess the level of stripping.
Rolling Bottle Test	Aggregate are coated with bitumen and covered with water in glass jars. The jars are rotated so that the contents are agitated. Periodically, the coating of the stones is estimated visually.
Net Adsorption Test	The test comprises two steps. First, bitumen is adsorbed onto aggregate from a toluene solution, the amount of bitumen remaining in solution is measured, and the amount of bitumen adsorbed to the aggregate is determined. Second, water is introduced into the system, bitumen is desorbed from the aggregate surface, the bitumen present in the solution is measured, and the amount remaining on the aggregate surface is calculated. The amount of bitumen remaining on the surface after desorption is termed net adsorption.
Wilhelmy Plate Test and Universal Sorption Device for Surface Free Energy	The principle behind using the concept of surface free energy is that the cohesive bonding within bitumen and the adhesive bonding between bitumen and aggregate are related to the surface free energy of the bitumen and aggregate. The bitumen surface free energy is determined by using a Wilhelmy plate test, where the dynamic contact angle between bitumen and a liquid solvent is measured. The surface free energy of aggregate is measured by using a universal sorption device developed at Texas A&M University.

Pneumatic Pull-Off Test	Binder, containing 1.0% by weight of glass beads, is applied to a porous disk, which is then pressed onto a glass plate. The glass beads are used to control the thickness of the bitumen film and do not appear to have any effect on the results. The pressure necessary to de-bond the conditioned specimen at 25° C is measured with a pneumatic adhesion tester.
Film Stripping Test (California Test 302)	This is a modified version of test procedure AASHTO T182 (Coating and Stripping of Aggregate/Bitumen Mixtures). 60g mass of aggregate coated with bitumen is placed in an oven for a certain time. The sample is then cooled and placed in a jar which rotates. The sample is removed and the percentage of stripping is estimated when the jar is viewed under fluorescent light. The results are reported in terms of the percent total aggregate surface stripped.

Table 4-2: Moisture Sensitivity Test on Loose Samples

As mentioned earlier a simulative test should take at least the “Internal”, “Traffic”, and “Environment” factors into account. The above tests fail to take into account the pore pressure effect and traffic action and therefore may not be a suitable candidate for the proposed TSCS.

4.2.2 *Moisture Sensitivity Test on Compacted Mixtures*

The tests detailed below summarises moisture sensitivity tests that can be conducted on laboratory compacted specimens or field cores or slabs. (Solaimanian et al, 2003; Airey et al, 2005; Delorme et al, 2007; Schram et al, 2012).

1) Immersion – Compression Test ASTM D1075 (1949 and 1954) and AASHTO T165-55

Two groups of compacted specimens are used in this test method. One group is submerged in a 5°C water bath for 4 days for conditioning and the other group is maintained dry. Compressive strength is measured on specimens of both groups at 25°C. The average strength of conditioned specimens over that of dry specimens is used as a measure of moisture sensitivity of the mix. Most agencies in the US have used a 70% ratio as a passing limit.

2) Marshall Immersion Test

The conditioning phase of this test is identical to the Immersion-Compression test. However, Marshall Stability is used as a strength parameter rather than compressive strength.

3) Moisture Vapor Susceptibility

Two specimens are prepared and compacted. The compacted surface of each specimen is covered with an aluminum seal cap and a silicone sealant is applied around the edges to prevent the escape of moisture vapor. Following this, the assembly is left in an oven at 60°C with the assembly suspended over water for 75 hours. The specimen is then removed and tested immediately in the Hveem Stabilometer.

4) Repeated Pore Water Pressure Stressing and Double-Punch Method

To capture the water pore pressure effect, compacted specimens undergo cyclic stressing under water. Once cyclic water pressure inducement is complete, the tensile strength of the specimens is obtained by using the double-punch equipment.

5) Original Lottman Indirect Tension Test

The procedure requires one group of dry specimens and one group of conditioned specimens. Conditioning includes vacuum saturation and freeze-thaw cycling or alternatively thermal cyclic conditioning. Specimens are both tested for tensile resilient modulus and tensile strength using indirect tensile equipment. The severity of moisture sensitivity is judged on the basis of the ratio of test values for conditioned and dry specimens.

6) Modified Lottman Indirect Tension Test Procedure (AASHTO T283)

This test is currently the most widely used procedure. The test is similar to the original Lottman with a few exceptions. One of the modifications is that the vacuum saturation is continued until a saturation level between 70% and 80% is achieved. In comparison with the original Lottman procedure that requires a set time of 30 minutes. Another change is in the test temperature and loading rate for the strength test. At least six specimens are prepared and compacted. The compacted specimens are expected to have air voids between 6.5% and 7.5%. Half of the compacted specimens are conditioned through a freeze (optional) cycle followed by a water bath. The other three samples remain unconditioned. All of the samples are brought to a constant temperature, and the indirect tensile strength is measured on both dry (unconditioned) and conditioned specimens.

7) Tunnicliff–Root Test Procedure (ASTM D4867)

ASTM D4867, “Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures,” is comparable with AASHTO T283. In both methods, the freeze cycle is optional. However, curing of the loose mixture in a 60°C oven for 16 h is eliminated in the ASTM D4867 procedure.

8) Texas Freeze–Thaw Pedestal Test

The hot mix prepared is kept in the oven at 150°C for 2 hours and stirred for temperature uniformity every hour. At the end of 2 hours, the mix is removed from the oven and cooled to room temperature, reheated to 150° C and then compacted to form a briquette. The briquette is cured for 3 days at room temperature and placed on a pedestal in a covered jar of distilled water. It is then subjected to thermal cycling of 15 hours at –12°C, followed by 9 hours at 49°C. After each cycle, the briquette surface is checked for cracks. The number of cycles required to induce cracking is a measure of water susceptibility (typically 10 freeze–thaw cycles).

9) Hamburg Wheel-Tracking Device

This device measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of an asphalt concrete specimen that is immersed in hot water. Each steel wheel passes 20,000 times or until 20mm of deformation is reached. The measurements are customarily reported versus wheel passes.

10) Environmental Conditioning System (ECS)

The procedure was designed to determine the moisture susceptibility of compacted asphalt mixtures under conditions of temperature, moisture saturation and dynamic loading similar to those found in pavements. In this procedure, a membrane-encapsulated specimen is subjected to cycles of temperature, repeated loading, and moisture conditioning.

The conditioning involved:

- Water at partial vacuum of 254 mm Hg or 508 mm Hg for 30 minutes
- 3 hot cycles @ 60°C for 6 hours
- One freeze @ -18°C for 6 hours.
- Resilient modulus (stiffness) of the samples will be determined. If the ratio (ratio of the conditioned and unconditioned resilient moduli) falls below 0.8, the mixture will be considered as marginal. If the ratio is equal to or above 0.8, the mixture will be considered as a well-performing mix.

11) Duriez Test

This is the test that is used within the scope of French standardization practices. The asphalt mixtures are compacted in a cylindrical mould. A set of specimens are conserved without any controlled temperature immersion (18°C) or relative humidity immersion while the other group is held immersed.

Two compaction efforts:

- D < 14 mm, H 190 mm, 60 kN, 5 min
- D > 14 mm, H 270 mm, 180 kN, 5 min
- Stored at 18°C, 7days: in air (50 % moisture) or in water at 18°C for 7days compression at 18 and 1mm/s

12) Moisture Induced Sensitivity Test (MIST)

The Moisture Induced Sensitivity Test (MIST) as shown in Figure 4-1 was performed on plant produced surface mixes in Iowa. Gyratory compacted specimens are placed in water chamber at 60°C. A bladder inside the chamber inflates, creating a pressure of 40 psi. The inflation is repeated for up to 3,000 cycles. The density of the conditioned specimens is measured and the specimen is loaded in indirect tension. The ratio of MIST conditioned to unconditioned sample strengths is recorded as well as the amount (%) of swelling, measured in percent change in air voids. This test is being evaluated in the USA and has found favor as it is thought to simulate the action of traffic (pressure pulsing) and uses an immersed sample.

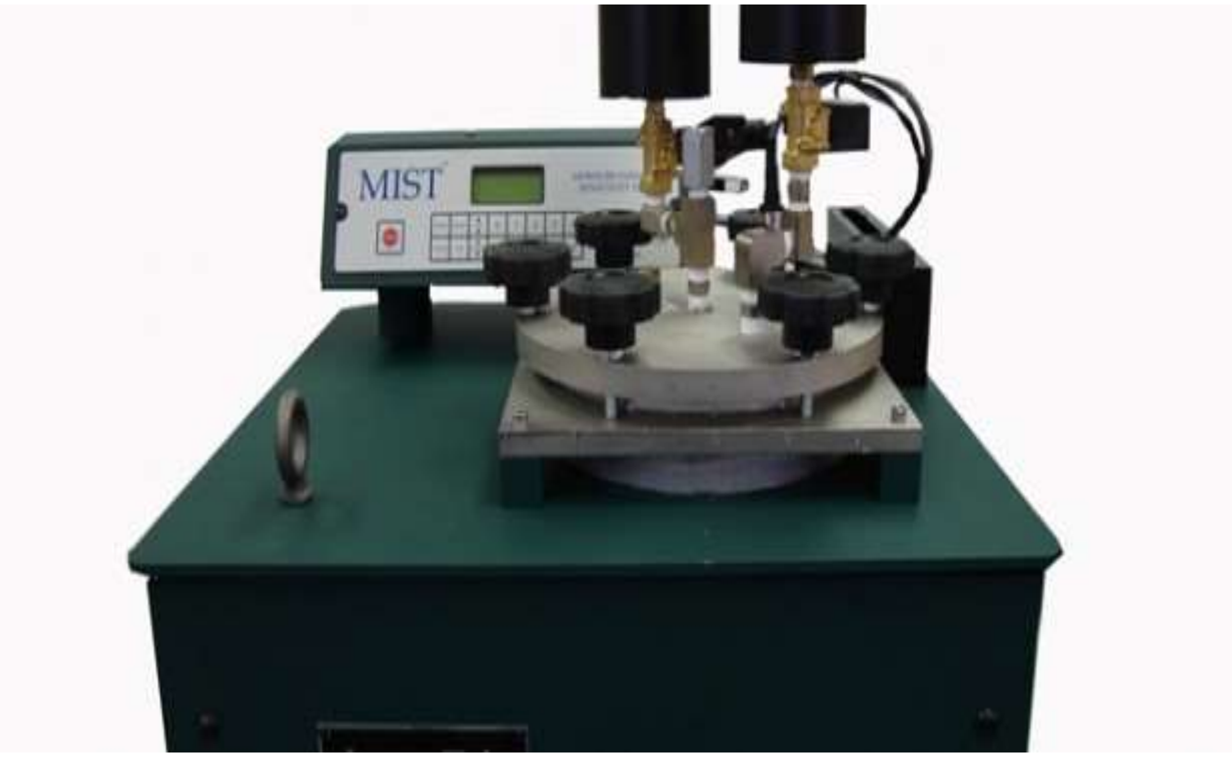


Figure 4-1: MIST Equipment

13) Asphalt Pavement Weathering System (APWS)

This protocol has been promoted by PRI Asphalt Technologies Inc. (http://www.priasphalt.com/). It works in similar principles as those adopted for laboratory ageing of asphalt roofing. Figure 4-2 shows the concept of the APWS while Figure 4-3 shows a typical test set-up for APWS.

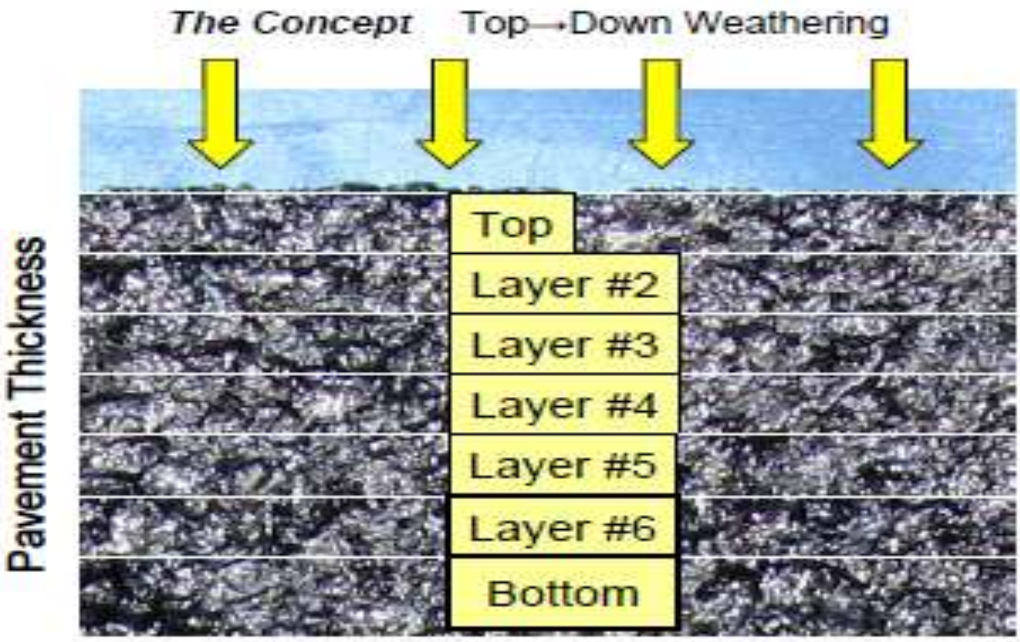


Figure 4-2: Concept for the APWS

The APWS uses lamps containing quartz discharge tubes with tungsten filaments which provide a mix of radiation similar to natural sunlight (UVA, UVB, visible and infrared radiation). The special glass of the bulb also filters out the portion of the generated radiation which is not contained in natural sunlight.

Accelerated Weathering with Temperature Flexibility:

- Chamber 50-160°F
- Specimen Surface 50-180°F

Figure 4-3: APWS Test Set-up

Cycle Flexibility: Typical Combination

- Sunlight only
- Sunlight + Rain
- Rain Only
- Dark Only
- Dark + Rain
- Sunlight/Dark + Rain

Special Conditioning:

- Leachate (Water) Collection
- Water Options (fresh, salt, deionized)
- Varied specimen mounting
- Companion Sample Outdoor Weathering
- 10 Channel Temperature Monitoring & Recording
- Water Spray System Flexibility
- Chamber Partitioning (water only)
- Permeability (rate determinations)

Figure 4-4 shows a special conditioning using spray jets to apply water mist on the asphalt material.

Figure 4-4: Special Conditioning using the APWS

14) Saturation Ageing Tensile Stiffness (SATS)

SATS testing consists of initial saturation under vacuum prior to placing compacted asphalt core samples in a high temperature and pressure environment in the presence of moisture for an extended period of time. The stiffness modulus measured after the test divided by the stiffness modulus measured before the test (retained stiffness modulus), and the specimen saturation after the test (retained saturation), are used as an indication of the sensitivity of the compacted mixture to combined ageing / moisture effects.

The SATS test is based around the principle of combining ageing with moisture conditioning by conditioning pre-saturated asphalt mixture specimens at an elevated temperature (85°C) and pressure (2.1 MPa) in the presence of moisture for a duration of 65 hours. A pressure vessel is used to hold five nominally identical specimens (100 mm in diameter and 60 mm in thickness) in a custom-made specimen tray as shown in Figure 4-5.

Figure 4-5: SATS Test Equipment

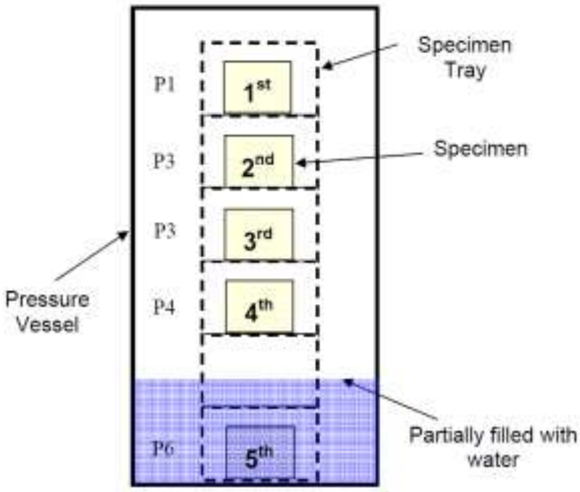


Figure 4-6: SATS Test Set-Up

The test protocol was developed with a primary aim to assess any risk to moisture induced damage of high modulus asphalts with low binder content. It has been included in Clause 953 of the UK Specification for Highway Works.

It should be noted that the majority of the tests mentioned above, with the exception of MIST, do not take into account the impact of traffic, more specifically the shear forces induced by accelerating, braking and turning of heavy vehicles which can accelerate wear. Therefore, the following section describes the tests that can potentially be used on asphalt mixtures.

4.3 Scuffing and Wear Tests

Detailed below are some tests commonly used to simulate wear effect (Solaimanian et al, 2003; Airey et al, 2005; Delorme et al, 2007; Schram et al, 2012 and Thom, 2014).

1) Pavement Testing Machine (PTM)

The method is described by EN 13863-4:2004. The machine has an electrically powered rotating axle with four wheels and adjustable rotating speed as depicted in Figure 4-7. The diameter of the test ring is about 6m and the machine is located in a closed room with controlled ventilation.

In this machine, particles from wear of pavement and tyres can be studied separately without interference of particles from exhausts. The machine accelerates the study; pavement types, car tyres, friction materials, driving speeds and temperatures can be varied.

The PTM test is a simulative test. However, one of the limitations of PTM is that the lateral movement of the wheels which creates more wear is not considered. In addition, the test needs to be modified to consider the pore pressure effect and moisture damage mechanism. It must be noted that to perform the test under saturation might be difficult.

Figure 4-7: Pavement Testing Machine

2) Tröger

Tröger is described by EN 1871:2000 Annex K and Norwegian Public Roads Administration and shown in Figure 4-8.

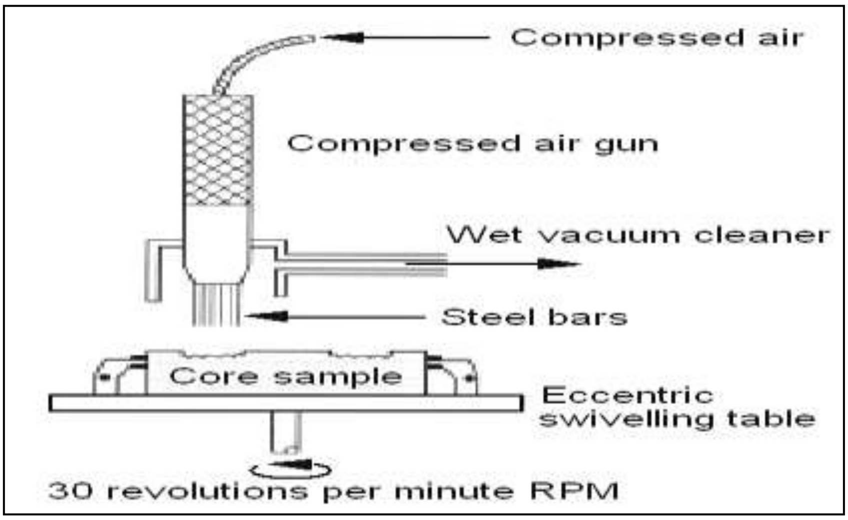


Figure 4-8: Tröger Test Equipment

This method was originally designed for testing abrasion of road marking materials but has also been used to determine the resistance of asphalt mixtures to wear caused by studded tyres. Samples with height of 30 mm and diameter 100 mm is mounted on an eccentric swiveling and rotating table with 30 rotations per minute. 52 steel needles, 2mm in diameter hammer the sample driven by a compressed air gun at 5 bars. This simulates the hammering and scratching influence of the tyre studs. Tröger test is not a simulative test and adaptation in the UK may not be realistic as the use of studded tyres is limited. In addition, it does not take into account the pore pressure effect and moisture damage mechanism.

3) Prall

The Prall method is described by EN 12697-16:2004 and depicted in Figure 4-9. It was developed to determine wear resistance of asphalt mixtures. The pavement sample with height 30mm and diameter 100mm is conditioned in water at 4-5ºC before it is put in a test chamber with 40 steel balls. The steel balls which are 12mm in diameter, hammer the sample driven by a stay rod which rotates with 950 RPM. Cooling water is flushed through the chamber with efficiency of 2 liters/min. Particles torn loose from the sample are washed out by the cooling water into a collector and finally the Prall value is calculated. Prall test is similar to the Tröger test. It is not a simulative test and the test adaptation in the UK may not be realistic since the use of studded tyres is limited. In addition, the test does not take into account the pore pressure effect and moisture damage mechanism.

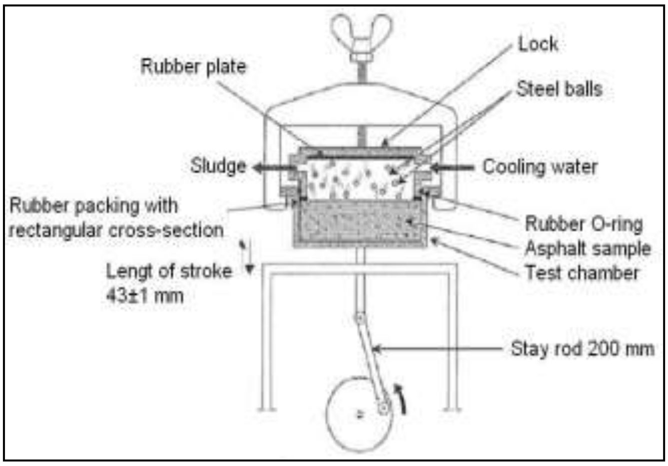


Figure 4-9: Prall Test

4) Scuffing Wheel Apparatus

Figure 4-10: Scuffing Wheel Apparatus

Scuffing-wheel apparatus consists of a loaded wheel which bears on a specimen held in a moving table. The table moves to and fro beneath the wheel with the axle of the wheel held at an angle of (20±l°) to the vertical plane perpendicular to the direction of travel. The test is described in TRL report 176 and is being currently used for the erosion measurements on the High Friction Surfacing. The test is simulative which will consider the traffic action however; it needs to be modified to consider the pore pressure effect and moisture damage mechanism. Furthermore, there could be issue with accumulation of heat due to friction between tyre and the surface and this may exacerbate the amount of raveling.

5) The ARTe (the Aachener Raveling Tester)

The ARTe is one of the four types of equipment described in the present version of a new technical specification which is being developed by Technical committee CEN/TC227/WG1. The test is performed in a temperature controlled room which is ventilated and capable of allowing the temperature of the slab fixation box and the average temperature of the air draught at tens of centimeters from the slab to be fixed at a temperature of (20 ± 2)°C throughout the duration of the test. During the test, the lateral moving table travels 600 times forwards and backwards over the slab. During that time, the wheels are rotating with (47 ± 1) rpm. After half the number of load repetitions, the slab fixation box will be rotated 180º. After finishing the test, the slab will be removed from the slab fixation box. Loose material shall be removed from the surface of the slab using a vacuum cleaner. The surface shall be inspected visually and any differences between the initial and end surface will be reported. The ARTe test gives repeatable results and most of the tested mixtures behave as expected. The confidence in the test result is good because it is a realistic yet relatively simple test. A study conducted by Belgian Road Research Centre concluded that the ARTe test is the most suitable laboratory test to simulate the effect of shear forces induced by traffic. However, it needs to be modified to consider the pore pressure effect and moisture damage mechanism. Furthermore, there could be issues with accumulation of heat due to friction between tyre and the surface which may exacerbate the amount of raveling. The test equipment is depicted in Figure 4-11.

Figure 4-11: The ARTe (the Aachener Raveling Tester)

6) The DSD (the Darmstadt Scuffing Device)

The DSD is one of the four types of equipment described in the present version of a new technical specification which is being developed by Technical Committee CEN/TC227/WG1. A tyre is lowered with a controlled force onto the surface of a test plate (260 mm x 260 mm) while the plate performs a combination of translations and rotations. This simulates the mechanical effect of vehicles on the wearing course when they are accelerating, braking or turning. The loss of material measured in the test is a direct measure of the resistance to raveling. The test is simulative and considers the traffic action. However; it needs to be modified to consider the pore pressure effect and moisture damage mechanism. Furthermore, there could be an issue with accumulation of heat due to friction between tyre and the surface and this may exacerbate the amount of raveling. Figure 4-12 shows the Darmstadt Scuffing Device.

Figure 4-12: The Darmstadt Scuffing Device

7) The RSAT (the Rotating Surface Abrasion Test)

The RSAT is one of the four types of equipment described in the present version of a new technical specification which is being developed by Technical committee CEN/TC227/WG1. The RSAT is shown in Figure 4-13. The RSAT method was developed to reproduce the scuffing damage as it occurs on real life pavement roads.

Figure 4-13: The Rotating Surface Abrasion Test

The motion of the wheel in relation to the test specimen is as shown in Figure 4-13. The motion of the arm must be constant with the guiding arms playing a part in ensuring constancy. The rotation of the test specimen shall be caused by the turning forces of the tyre-road action. In order to stimulate the shear stresses, the slab shall be blocked in one direction by a brake. Either slabs or cores can be tested. The slab shall be an octagon shape. The length and width shall be approximately 500 mm x 500 mm. The thickness can vary between 30 mm and 60 mm. Cores shall have a diameter of (150 ± 1 mm) and a height between 30 mm and 60 mm. Three cores can be tested in one test. The cores shall be fixed in an octagon shaped mould. During the test, all loose material shall be removed from the surface of the specimen using a vacuum cleaner. By separating mineral aggregates from the rubber, the aggregate loss during the test shall be determined. The test is simulative and considers the traffic action however; it needs to be modified to consider the pore pressure effect and moisture damage mechanism. Furthermore, there could be issue with accumulation of heat due to friction between tyre and the surface and this may exacerbate the amount of raveling.

8) The Triboroute

The Triboroute is one of the four types of equipment described in the present version of a new technical specification which is being developed by Technical committee CEN/TC227/WG1. The Triboroute shall be composed of: a braced vertical column supporting the load applicator mounted on a classical hydraulic press and a roller-mounted horizontal table. This table shall be able to accommodate a parallel piped specimen (185 mm by 247 mm) or an in situ core sample up to 300 mm in diameter. Figure 4-14 shows the Triboroute.

The test of resistance to tangential forces shall consist of applying an average load that represents the loading of a truck tyre on the surfacing material. The sliding of tread rubber shall be obtained through the vertical displacement rate. The load applicator representing the tyre shall be a logarithmic shaped block (LSB) with a width of 140 mm covered by an 8 mm thick rubber layer with rheological characteristics close to those of tyre treads. The test is simulative and considers the traffic action however; it needs to be modified to consider the pore pressure effect and moisture damage mechanism. Furthermore, there could be issue with accumulation of heat due to friction between tyre and the surface and this may exacerbate the amount of raveling.

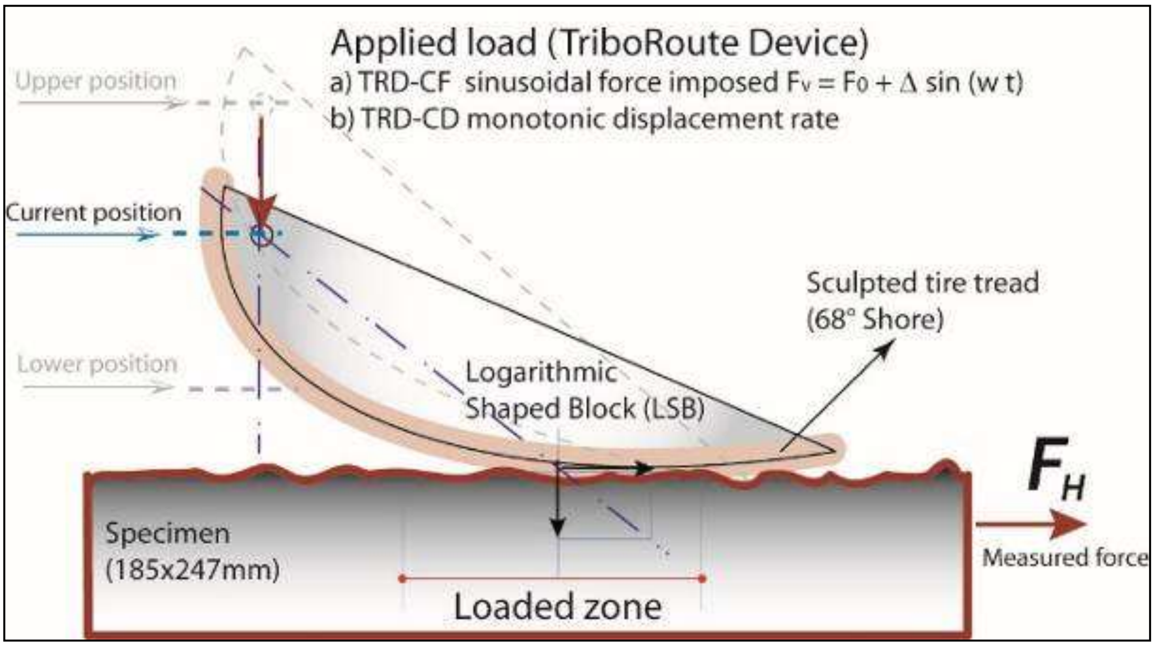


Figure 4-14: Principle of the Triboroute Test Equipment

9) Model Mobile Load Simulator (MMLS3)

MMLS3 test has been trialed and used in a number of countries in Europe, South Africa, USA and Australia; details can be found from this website: http://www.mlstestsystems.com/.

MMLS3 consists of four recirculating axles, each with a single 300 mm diameter wheel as shown in Figure 4-15. The wheels can be laterally displaced across 150 mm in a normal distribution about the center line to simulate traffic wandering. The tyres may be inflated up to a pressure of 800 kPa. Axle loads varying between 2.1kN and 2.7kN are possible. The axle loads are automatically kept constant at a predetermined value by the special suspension system. Nominal wheel speed is 2.5 m/s, applying about 7200 loads per hour. A single 1.5 kW variable speed motor drives the chain of four wheels. This test has been considered as full scale testing which can be carried out in laboratory (core samples) and directly on pavement. Test can also be done in dry or wet condition. An environmental chamber can be utilized to maintain temperature of samples or pavement during testing. Many have regarded this test as simulative to loading anticipated on roads and airfield pavements, and specifications exist for its adoption during construction works. The flexibility offered by this test is considered to be a candidate for simulative laboratory durability test. The laboratory test bed is shown in Figure 4-16. Section 9 discusses the MMLS in details.

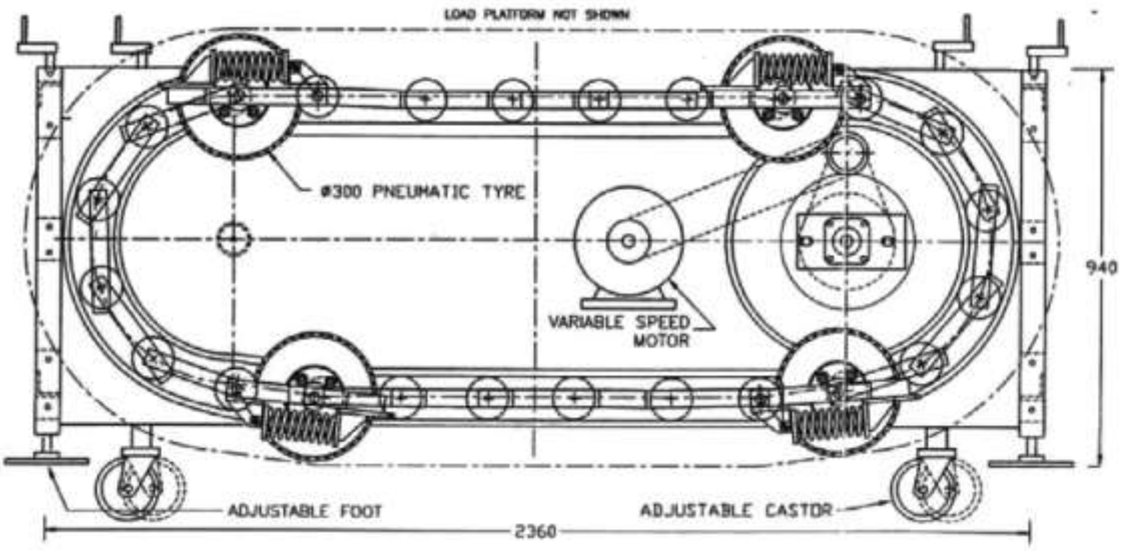


Figure 4-15: Model Mobile Load Simulator (MMLS3)

Figure 4-16: Laboratory Test Bed for the MMLS

5 ACCELERATED LABORATORY AGEING AND DURABILITY FOR THIN SURFACINGS

Pavement structures need to be durable. This section details the adopted approach used in this project in simulating and assessing the laboratory ageing and durability for thin surfacings. The Saturated Ageing Tensile Stiffness (SATS) test was one of the first protocols to simulate both ageing and moisture susceptibility of asphalt mixtures in a single test. These are the two primary mechanisms for durability of asphalt mixtures. Moisture damage affects the performance and durability of asphalt mixtures as there is a loss of cohesion in the binder. In most cases, a result of moisture damage is the loss of adhesion between the aggregate and the binder. These factors act to decrease the stiffness and strength of asphalt mixtures which eventually affects the structural performance of the pavement.

The SATS test was originally developed at Nottingham Transportation Engineering Centre (NTEC) to simulate the ageing and moisture damage process of asphalt mixtures through the combined effects of high pressure, high temperature and water under laboratory test conditions. The test was able to show the decrease in stiffness due to ageing and moisture damage. The test was also able to identify and distinguish the quality of materials. The test application was limited to asphalt mixtures made up of low penetration grade (hard) bitumen typically 10/20 pen with high air voids (8%) as it could not be used to accurately assess the moisture damage of asphalt mixtures with high penetration grade (softer bitumen) at low air voids (<6%). The SATS test set-up including the major features and components are highlighted in Figure 5-1. The main feature of the SATS test consists of a well-insulated heated pressure vessel capable of holding five compacted asphalt specimens (100mm diameter by 60mm height). The SATS test set-up allows for simultaneous control of pressure and temperature. The test set up needs capabilities for the samples to be pre-saturated with water under vacuum. Full details of the SATS test procedure are detailed in Specification for Highway Works Clause 953 (November, 2008) or PPR 547.

The standard SATS test procedure is summarised below:

1. The unconditioned initial (indirect) stiffness modulus of each specimen at 20°C is determined at standard test conditions in the Nottingham Asphalt Tester (NAT) in accordance with BS EN 12697-26, Annex C (124ms rise time, 5µm peak transient horizontal diametral deformation).
2. The dry mass of specimens is determined by weighing.
3. The specimens are then immersed in distilled water at 20°C and saturated using a residual pressure of 33 kPa (i.e. 68 kPa below atmospheric pressure) for 30 minutes.
4. The percentage saturation is determined by weighing the wet mass of each specimen. This is called ‘initial saturation’.
5. The pressure ageing vessel (PAV) is partially filled with distilled water until the level is between the fourth and fifth specimens (P4 and P5 as seen in Figure 5-1). Before placing the specimens in the PAV, the temperature of the water and the pressure vessel is maintained at 85°C for a minimum of 2 hours.
6. The saturated asphalt specimens are placed into the pressure vessel, the vessel is sealed and the pressure is gradually increased to 2.1 MPa.
7. The vessel’s temperature and pressure are kept at 85°C and 2.1 MPa respectively for 65 hours).
8. After 65 hours, the target vessel temperature is reduced to 30°C for 24 hours to cool down. Following this, the air pressure is gradually released. After the vessel has achieved atmospheric pressure, it is opened and the specimens are removed. Each specimen is then surface dried and weighed in air. The proportion saturation (in per cent) is calculated and documented as ‘retained saturation’.
9. The specimen’s temperature is brought down to 20°C and the conditioned final stiffness modulus is determined using a NAT in accordance with BS EN 12697-26.
10. The dimensions are checked once more to ascertain if the specimen has deformed significantly.
11. From the known values of initial and final modulus, the ‘retained stiffness modulus’ is calculated as the ratio of final to initial modulus. This is termed the SATS Durability Index and Clause 953 requires for this value to be above 80% for the mixture to be deemed satisfactory.

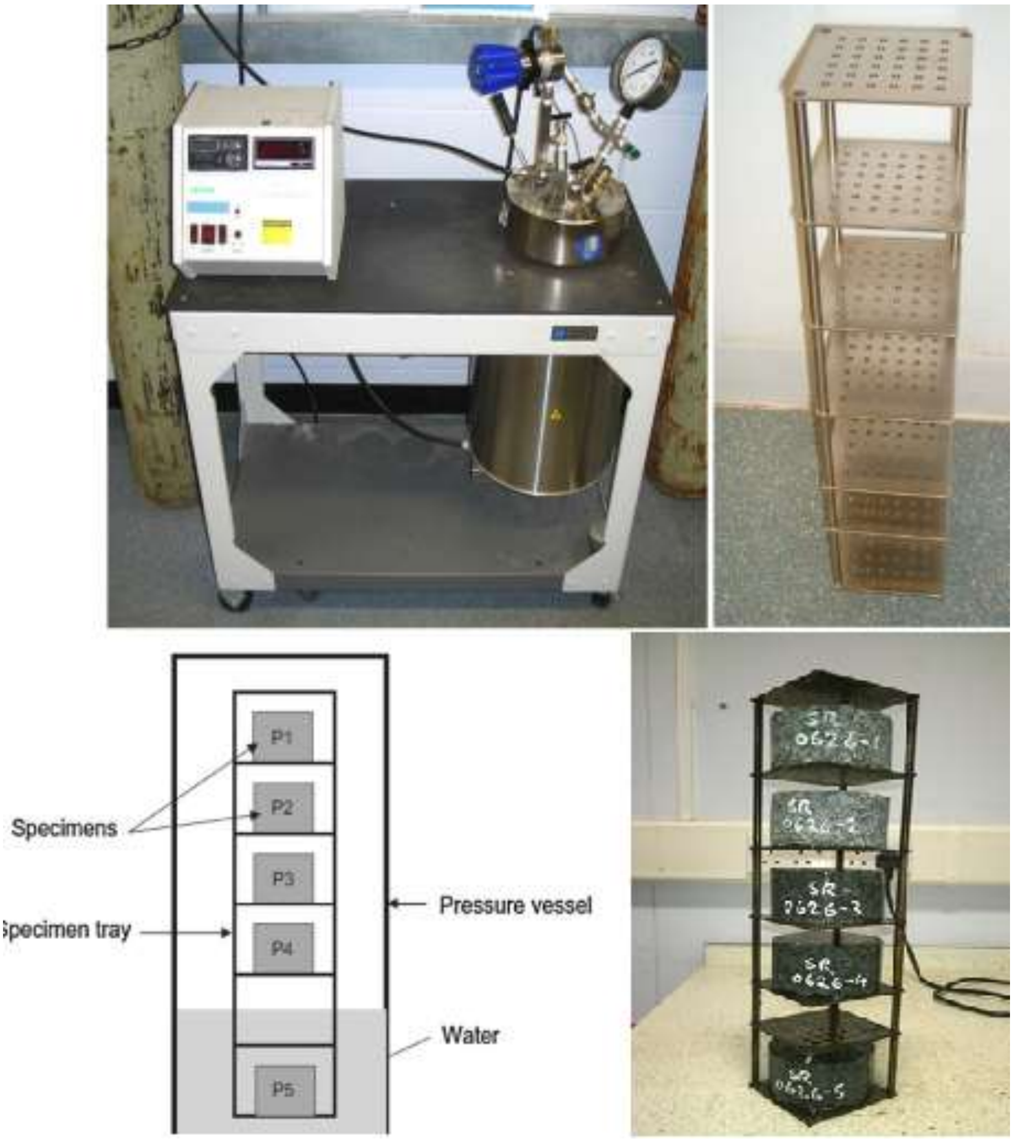


Figure 5-1: SATS Test Configuration

5.1 Modified SATS Test Protocol

The standard SATS test protocol was quite successful for the asphalt mixtures tested which comprised low bitumen content, high air voids and high stiffness. An alternative test approach was needed to take into account other mixture types that particularly have lower stiffness, lower air void contents and higher penetration grade binders (softer bitumen) or polymer modified binders. The overall idea was to widen the capability of the SATS test to take into account a wide range of asphalt mixtures as it was found that the standard SATS test protocol was too aggressive for materials with lower stiffness values. A protocol was needed that would prevent risk of irreversible damage to the mixture. The Modified SATS test method makes use of the same equipment and test set-up as shown in Figure 5-1.

The modified SATS test protocol follows the same procedure with the standard SATS test protocol except for the following changes as detailed below:

- The saturated asphalt specimens are placed in the vessel and a reduced pressure of 0.5 MPa is used as opposed to 2.1 MPa in the standard SATS test protocol.
- The vessel's temperature and pressure are kept at 85°C and 0.5 MPa for 24 hours. A reduced duration is used in contrast to 65 hours used in the standard SATS.

5.2 Review of Key Points

To summarise, the major changes between the standard and Modified SATS test protocols are the reduced duration of the test to 24 hours and reduced pressure of 0.5 MPa which the specimens encounter inside the pressure vessel. The detailed study is presented in PPR 535.

A review of key points with respect to the standard and Modified SATS test protocols are detailed below.

1. The standard SATS test protocol was quite successful for the asphalt mixtures tested which comprised of low bitumen content, high air voids and high stiffness.
2. The standard SATS test protocol was found to be too harsh for specimens with higher penetration grade binders such as the 40/60 pen bitumen or above with lower air void contents (<6%).
3. An alternative test approach was needed to take into account other mixture types that had lower stiffness, lower air void contents and higher penetration grade binders (softer bitumen).
4. A Modified SATS test protocol was needed to take into account a wide range of asphalt mixtures and to widen the applicability of the test in order to prevent the risk of irreversible damage to certain mixtures.
5. In developing the Modified SATS test, parameters including pressure, temperature and duration were varied or used in combination to obtain a suitable test condition. It was observed that pressure was the most significant test parameter. The retained stiffness values increased due to a reduction in the pressure. The ideal pressure was found to be 0.5 MPa for the Modified SATS in comparison to 2.1 MPa for the standard SATS protocol. A reduction in temperature also increased the retained stiffness values as expected. A temperature of 85°C was found to be the ideal level in order to differentiate between good and poor aggregates with respect to moisture susceptibility. The effects of duration were found to be minimal. Therefore, it made sense for a shorter duration of 24 hours to be selected for the Modified SATS test so as to reduce time and cost.
6. Mixtures with high design air void content had high saturation and internal void connectivity. This is illustrated in Figure 5-3.
7. Mixtures containing different types of aggregates exhibited different susceptibility to saturation and moisture damage. Limestone aggregates performed more favourably than acidic granite aggregates.
8. Variations of filler type were found to affect the moisture damage performance of the granite aggregate asphalt mixtures. Substitution of 2% added limestone filler with hydrated lime dramatically improved the SATS results for the acidic granite Dense Bitumen Macadam (DBM) and high modulus base (EME2) mixtures, while substitution of the added limestone filler by granite filler resulted in lower retained stiffness values.
9. EME2 mixtures performed much better than asphalt concrete (AC) and DBM mixtures, under Modified SATS tests as depicted in Figure 5-2.
10. DSR tests on recovered cores after SATS tests shows significant ageing of the binder as a result of the conditioning procedure.
11. The Modified SATS test procedure to accommodate a wider range of asphalt mixtures was found to be 85°C temperature, 0.5 MPa pressure for 24 hours as detailed in Section 5.1.
12. Compared to AASHTO T283, the SATS test was found to be a more aggressive conditioning protocol, although both tests ranked mixtures in a similar order with respect to moisture damage. The increased severity of the SATS conditioning procedure results in larger reductions in stiffness modulus and therefore lower stiffness ratios.

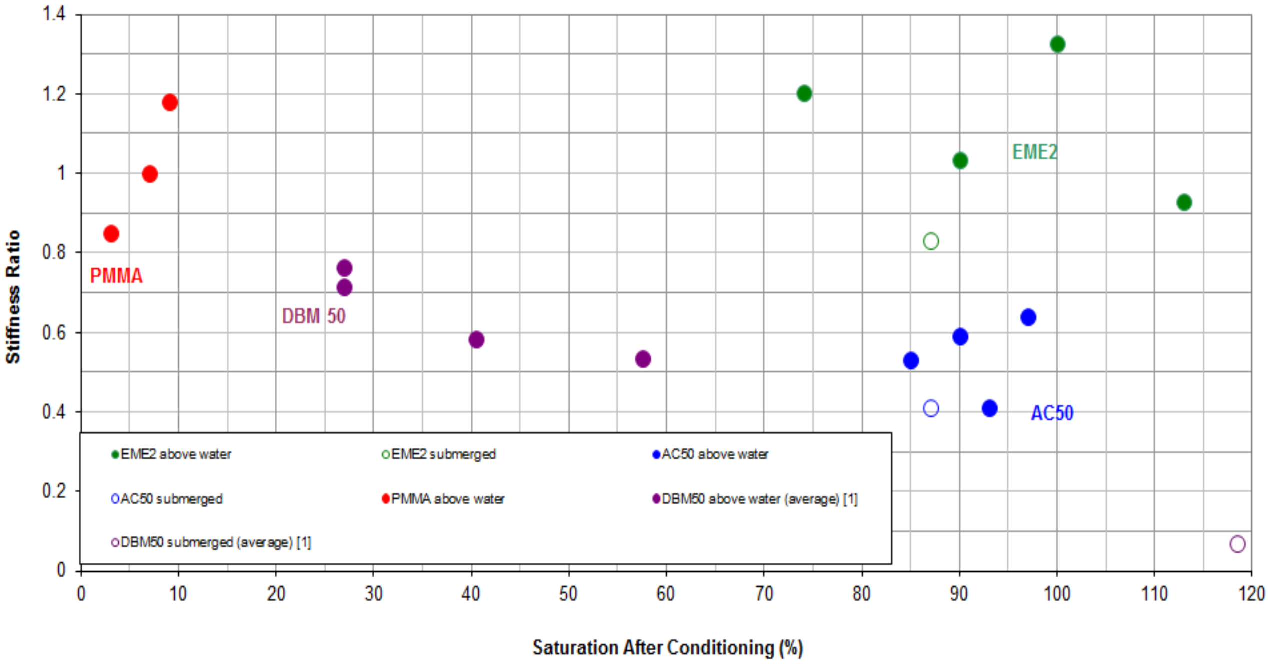
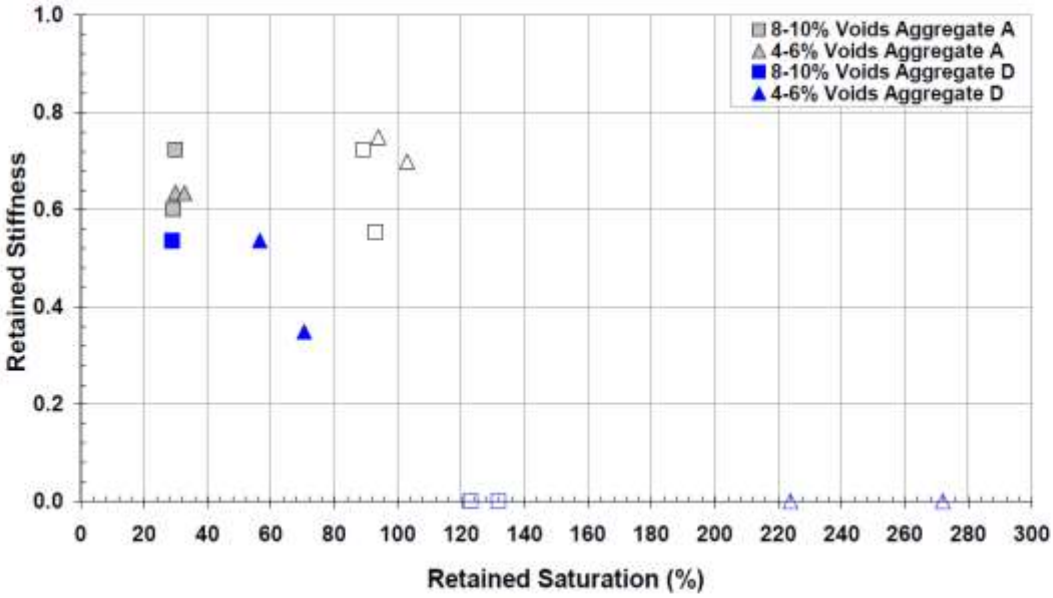


Figure 5-2: Modified SATS on some Dense Asphalt Mixtures



Note: Above-water specimens shown as solid; submerged specimens shown with white centres (of which several results are on the horizontal axis)

Figure 5-3: Modified SATS - Showing Influence of Air Voids on DBM (PPR 535)

From 5.2 shows a wide range of saturation conditioning for some dense low voided samples. Whilst the stiffness ratios can differentiate between different asphalt mixtures for different saturation levels it was considered necessary to improve the consistency for sample conditioning. The immersed sample, normally ignored for analysis in the Modified SATS protocol, was included for assessment in the current study. Samples of SMA 10 Surf 40/60 were manufactured to assess the durability of these samples; the Modified SATS test protocol was adopted. Table 5-1 and Figure 5-4 state the test results.

Core Reference	Air Voids (%)	Saturation Before Conditioning (%)	Saturation after Conditioning (%)	Average Saturation After Conditioning (%)	Unconditioned ITSM	Conditioned ITSM	Stiffness Ratios	Average Stiffness Ratios
Low Voids (<7%)								
562-1	4.5	10.0	19.0	12.3	6900	5600	0.81	0.85
562-2	4.8	10.0	15.0		6400	5500	0.86	
562-3	4.8	11.0	9.0		6100	5100	0.84	
562-4	4.8	8.0	6.0		6600	5900	0.89	
562-5	4.5	5.0	23.0	23.0	6100	5900	0.97	0.97
High Voids (>7%)								
598-1	14.1	32.0	20.0	20.0	5300	5900	1.11	1.06
598-2	13.5	34.0	21.0		5500	5300	0.96	
598-3	14.2	36.0	17.0		5200	5400	1.04	
598-4	12.1	37.0	22.0		5300	6000	1.13	
598-5	12.5	33.0	39.0	39.0	5600	6000	1.07	1.07

Table 5-1: Task 1 – Modified SATS Protocol on SMA Samples

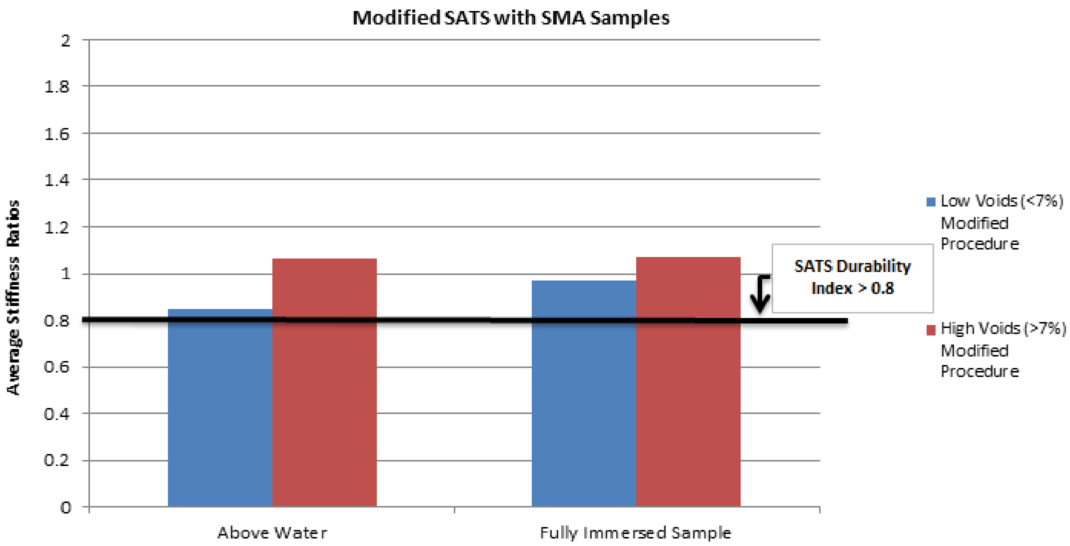


Figure 5-4: Stiffness Ratios for Modified SATS on SMA Samples

The results show that for SMA mixtures, the Modified SATS was not sensitive to air voids. All sample sets showed good resistance to moisture and ageing. Furthermore, the stiffness ratios were within a narrow range of 0.8 to 1.2. The immersed sample showed similar results for the high and low voided samples with respect to the stiffness ratio. However, this was based on one fully immersed sample for each set. To assess the consistency of the test results, it was proposed to develop a new test with three immersed samples as detailed in Section 6.

6 ACCELERATED DURABILITY TEST RESULTS USING THE IMMERSED AGEING TEST

6.1 Introduction

Based on findings from PPR 535, it was decided that Modified SATS should be mainly conducted in accordance with principles stated in Section 5.1 using an SMA 10 Surf 40/60 except using a new methodology which involved fully immersing three samples as depicted in Figure 6-1. This new methodology is called Immersed Ageing Test (IAT). This was conducted in order to ascertain the durability and ageing characteristics of the samples above and below water and to see if the immersed samples could provide consistent results.

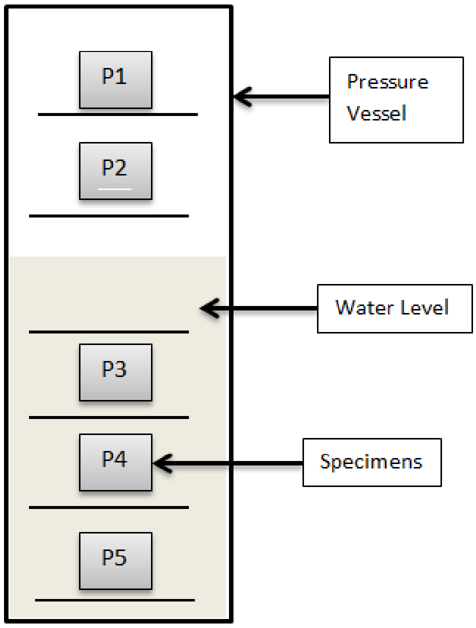


Figure 6-1: Test Set-up Showing Three Immersed Samples for IAT

Table 6-1 shows the material composition and limits for the SMA 10 Surf 40/60 asphalt material used in producing samples for IAT testing with both the IAT (0.5MPa, 24hours, 85°C) and IAT Extended (2.1MPa, 65hours, 85°C) for comparison. A similar aggregate composition and binder content was adopted for SMA 10 Surf PMB, except that cellulose fibre was not added to the mixture. Figure 6-2 presents the test matrix followed in the study.

Sieve (mm)	Envelope (% Passing)	Target (% Passing)
14	100	100
10	90-100	95
6.3	30-50	40
4	25-42	30
2	20-32	26
0.500	14-20	14
0.063	7-12	9.5
Binder Type (40/60 pen) – 6.5%		
Cellulose Fibre – 0.3%		

Table 6-1: Material Composition and Limits for SMA Samples for IAT

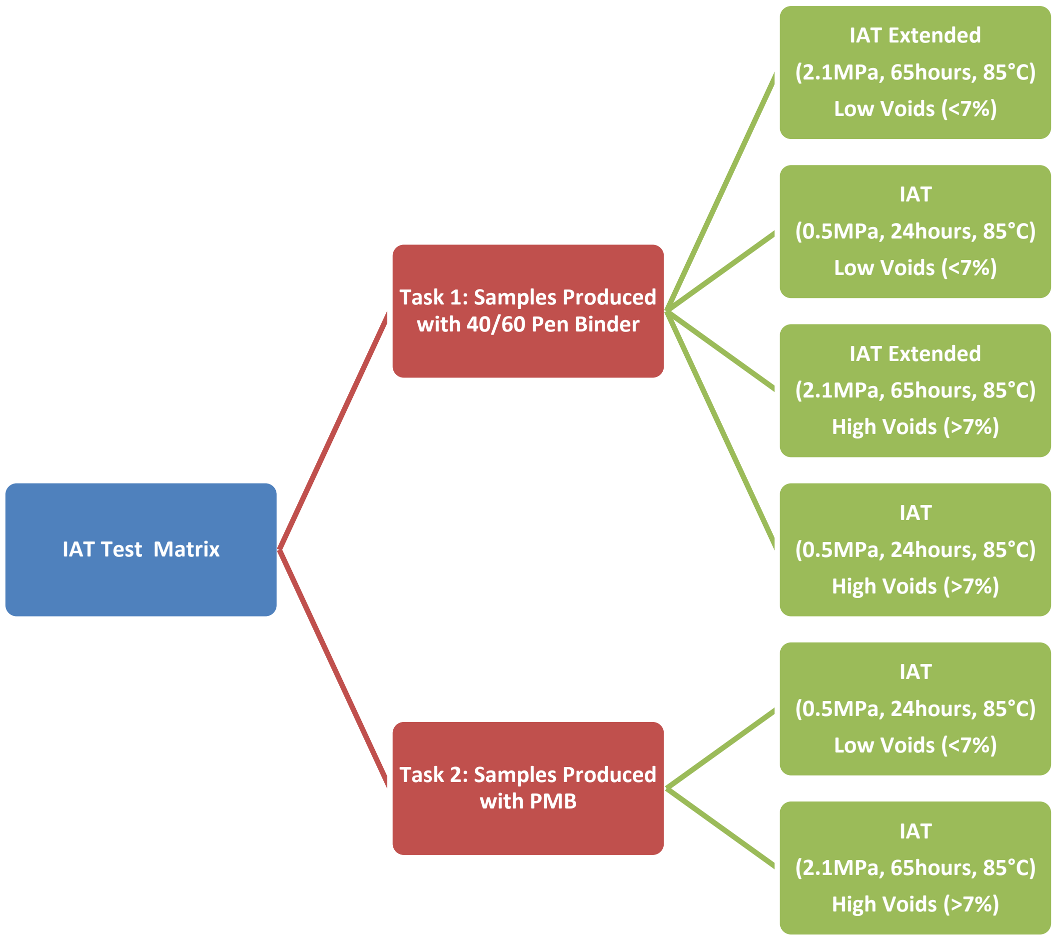


Figure 6-2: IAT Matrix for SMA 10 Surf Samples

6.2 IAT and IAT Extended Test Results

The ratios of the stiffness were measured by indirect tension on cylindrical specimens in accordance with BS EN 12697-26: Procedure C before and after conditioning. The results are presented below.

6.2.1 *Task 1: IAT and IAT Extended Results*

Task 1 followed the same procedure for Modified SATS as detailed in Section 5.1 on SMA 10 Surf samples, except that three samples were fully immersed and saturated in water inside the pressure vessel as opposed to one fully immersed sample. This was introduced to better understand the combined influence of moisture and ageing on durability of the produced asphalt mixtures and to improve consistency. The test set-up for the 3 fully immersed samples is as shown in Figure 6-1. Table 6-2 presents detailed test results from Task 1.

The mixtures with high air voids (>7%) had reduced stiffness ratios in comparison with the mixtures with low air voids (<7%) as seen in Figure 6-3. This suggests the conditioning protocol was able to differentiate the relative performance between samples with high and low air voids. Figure 6-4 and Figure 6-5 showed that there was little variability between the stiffness ratios and saturation after conditioning for the fully immersed samples for both the low voided and high voided mixtures respectively. These suggest that the protocol can provide consistent results and samples conditions, which is an improvement from Modified SATS method.
All the above findings provide better confidence in the conditioning process and the test results.

Core Reference	Air Voids (%)	Saturation Before Conditioning (%)	Saturation after Conditioning (%)	Average Saturation After Conditioning (%)	Unconditioned ITSM	Conditioned ITSM	Stiffness Ratios	Average Stiffness Ratios
IAT Extended (2.1MPa, 65hours, 85°C) – Low Voids (<7%)								
615-1	4.0	13.0	18.0	19.5	8400	11100	1.32	1.35
615-2	4.2	13.0	21.0		8300	11400	1.37	
615-3	4.2	9.0	32.0	37.3	8800	12200	1.39	1.34
615-4	4.2	12.0	42.0		8800	12000	1.36	
615-5	4.2	17.0	38.0		8700	11100	1.28	
IAT (0.5MPa, 24hours, 85°C) – Low Voids (< 7%)								
616-1	4.5	9.0	17.0	17.0	9400	11500	1.22	1.19
616-2	4.7	11.0	17.0		9400	10900	1.16	
616-3	4.8	9.0	36.0	33.3	9400	10700	1.14	1.22
616-4	4.5	11.0	34.0		8600	11200	1.30	
616-5	4.2	8.0	30.0		9900	12200	1.23	
IAT Extended (2.1MPa, 65hours, 85°C) – High Voids (>7%)								
625-1	7.2	24.0	42.0	38.5	5100	5200	1.02	1.00
625-2	6.8	20.0	35.0		5100	5000	0.98	
625-3	8.4	25.0	56.0	57.0	5100	4700	0.92	0.97
625-4	7.4	23.0	59.0		5300	5500	1.04	
625-5	7.6	24.0	56.0		4800	4500	0.94	
IAT (0.5MPa, 24hours, 85°C) – High Voids (>7%)								
626-1	7.8	20.0	19.0	15.0	5300	4000	0.75	0.79
626-2	7.1	15.0	11.0		5600	4600	0.82	
626-3	6.2	11.0	28.0	35.3	5500	4900	0.89	0.85
626-4	8.2	20.0	37.0		4900	4100	0.84	
626-5	8.7	19.0	41.0		5500	4600	0.84	

Table 6-2: Task 1 – IAT and IAT Extended Test Results

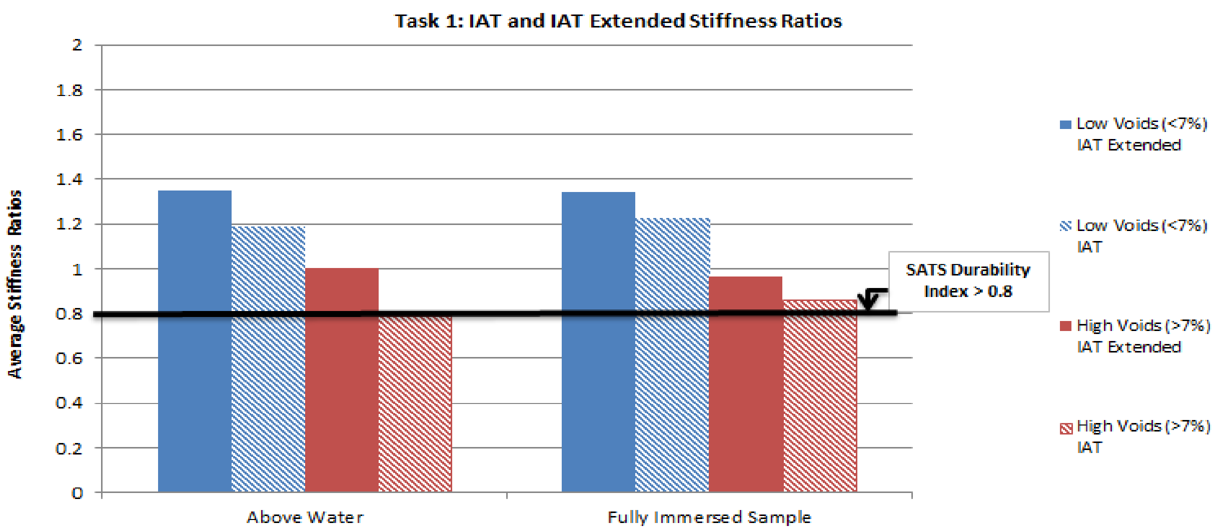


Figure 6-3: Task 1: IAT and IAT Extended Stiffness Ratios

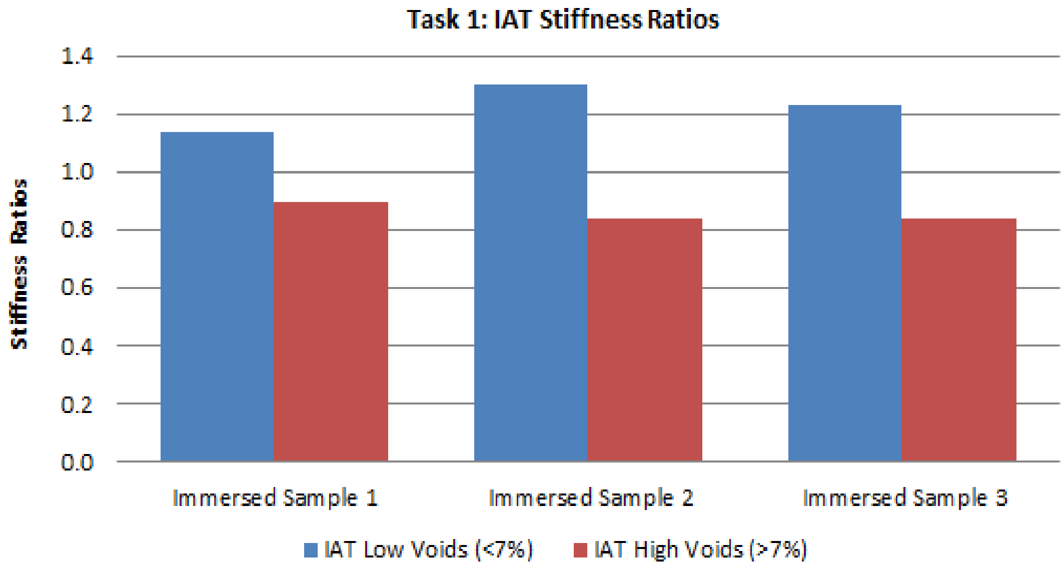


Figure 6-4: IAT Stiffness Ratios

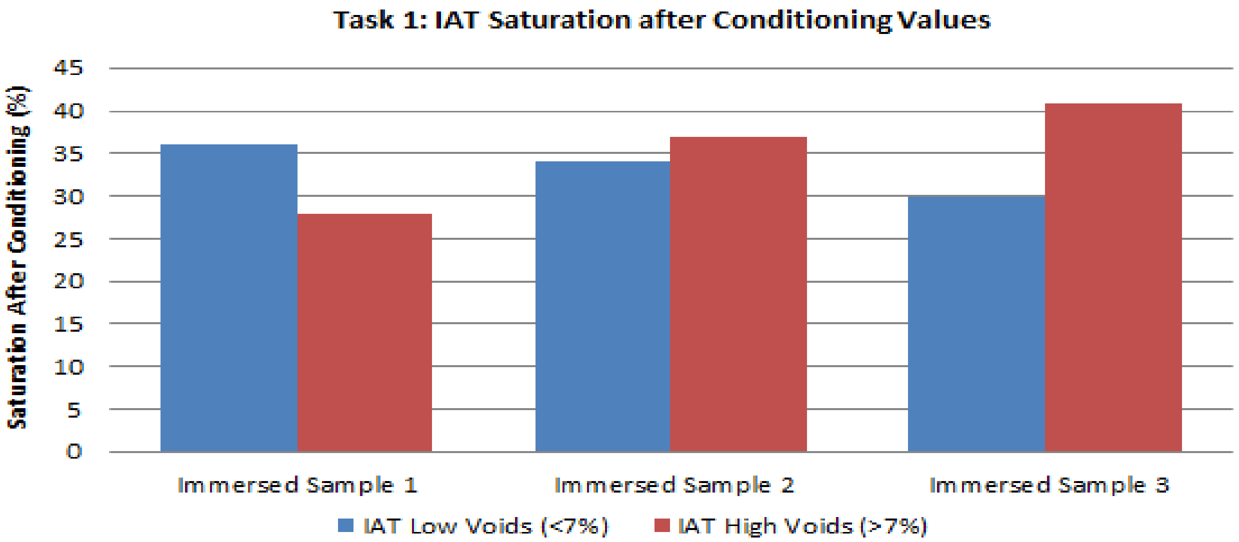


Figure 6-5: IAT Saturation after Conditioning

6.2.2 *Task 2: IAT using PMB Test Results*

In addition to the tests as detailed above in Section 6.2.1 on SMA 10 Surf using 40/60 pen paving grade bitumen, further samples were manufactured using a proprietary PMB material. Table 6-3 presents the test results for the IAT samples using PMB.

Core Reference	Air Voids (%)	Saturation Before Conditioning (%)	Saturation after Conditioning (%)	Average Saturation After Conditioning (%)	Unconditioned ITSM	Conditioned ITSM	Stiffness Ratios	Average Stiffness Ratios
IAT (0.5MPa, 24hours, 85°C) – Low Voids (<7%)								
685-1	4.1	9.0	26.0	24.5	3000	3300	1.10	1.16
685-2	4.6	10.0	23.0		2800	3400	1.21	
685-3	4.6	11.0	32.0	29.0	2600	3300	1.27	1.26
685-4	4.0	7.0	25.0		2700	3300	1.22	
685-5	4.4	8.0	30.0		2500	3200	1.28	
IAT (0.5MPa, 24hours, 85°C) – High Voids (>7%)								
686-1	14.6	21.0	21.0	22.0	2000	2400	1.20	1.08
686-2	13.9	22.0	23.0		2300	2200	0.96	
686-3	13.9	21.0	40.0	39.0	2200	2500	1.14	1.15
686-4	13.2	21.0	41.0		2300	2700	1.17	
686-5	12.8	19.0	36.0		2200	2500	1.14	

Table 6-3: Task 2 – IAT using a PMB Test Results

Figure 6-6 showed that there was virtually no reduction in stiffness values either at low voids or high voids for the IAT samples produced with PMB. The stiffness ratio ranged between from ≈1 to 1.28; this improvement in stiffness ratios may be attributed to the presence of polymer modified binders to enhance mixture resistance to ageing and moisture damage.

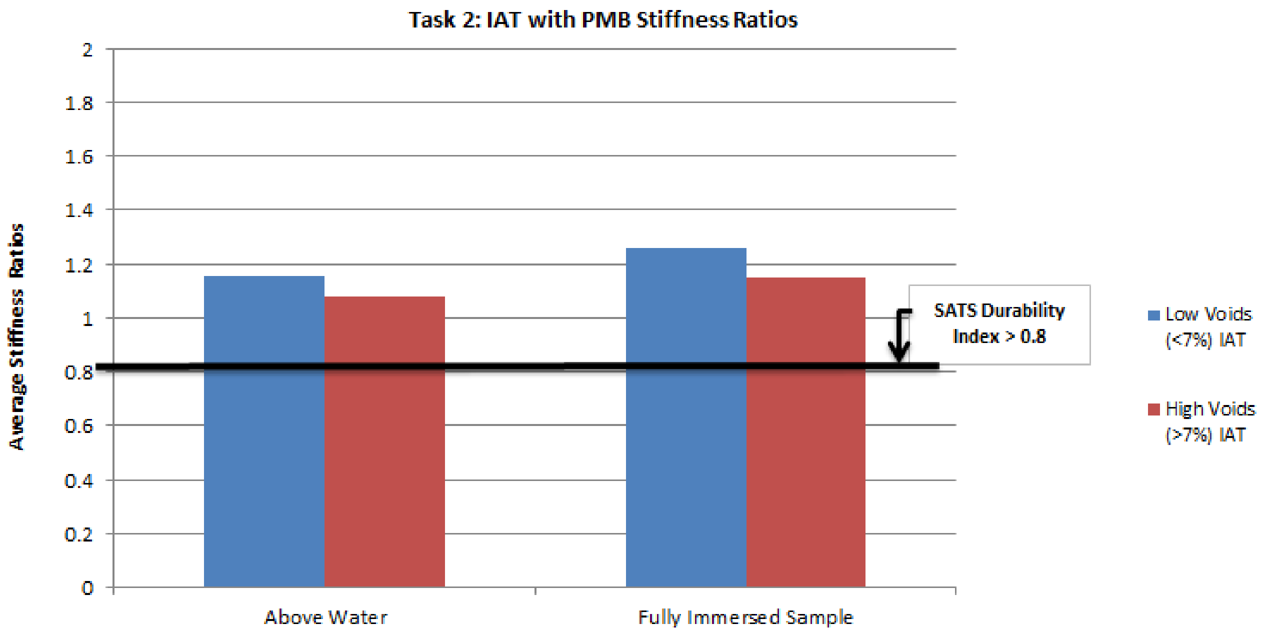


Figure 6-6: IAT with PMB Stiffness Ratios

Figure 6-6 and Figure 6-7 showed that there was little variability between the stiffness ratios and saturation after conditioning for the fully immersed samples for both the low voided and high voided mixtures respectively depicting similar trends as explained in Section 6.2.1.

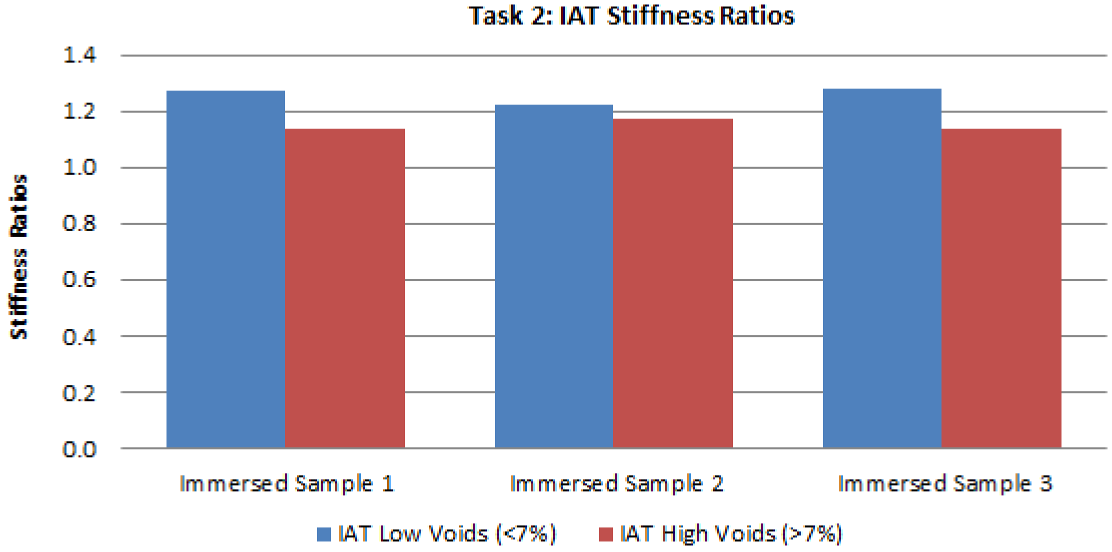


Figure 6-7: Task 2 – IAT Stiffness Ratios with PMB

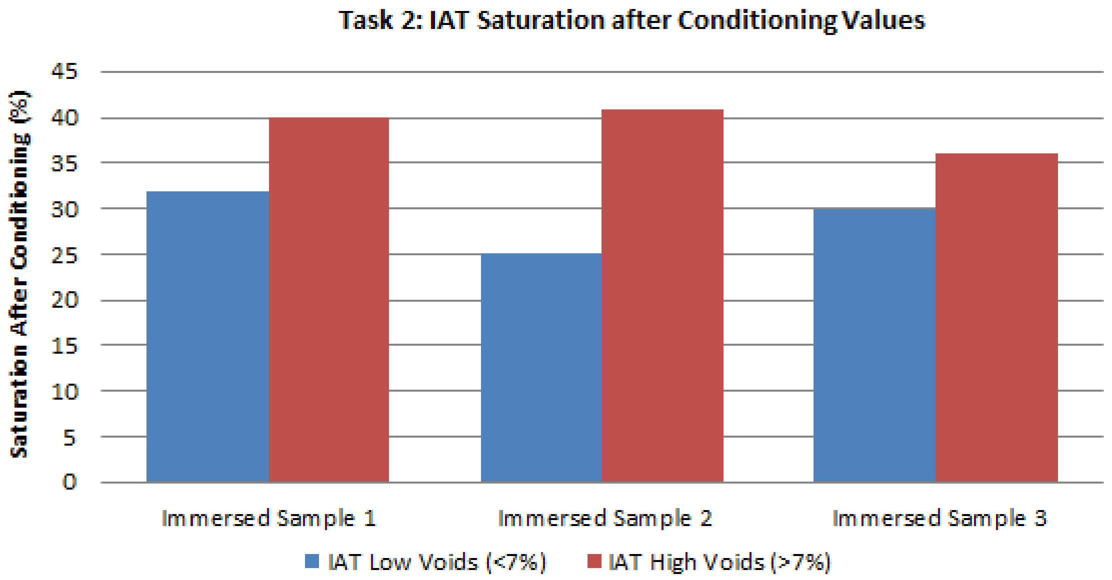


Figure 6-8 shows the post-conditioned state of a selection of samples indicating little or no visual damage to the samples after testing either using either the IAT or IAT Extended protocols. The above findings are consistent with the previous findings on SMA 10 Surf 40/60 and these suggest the suitability of the new protocol (IAT) for assessment of binder rich samples such as SMA.

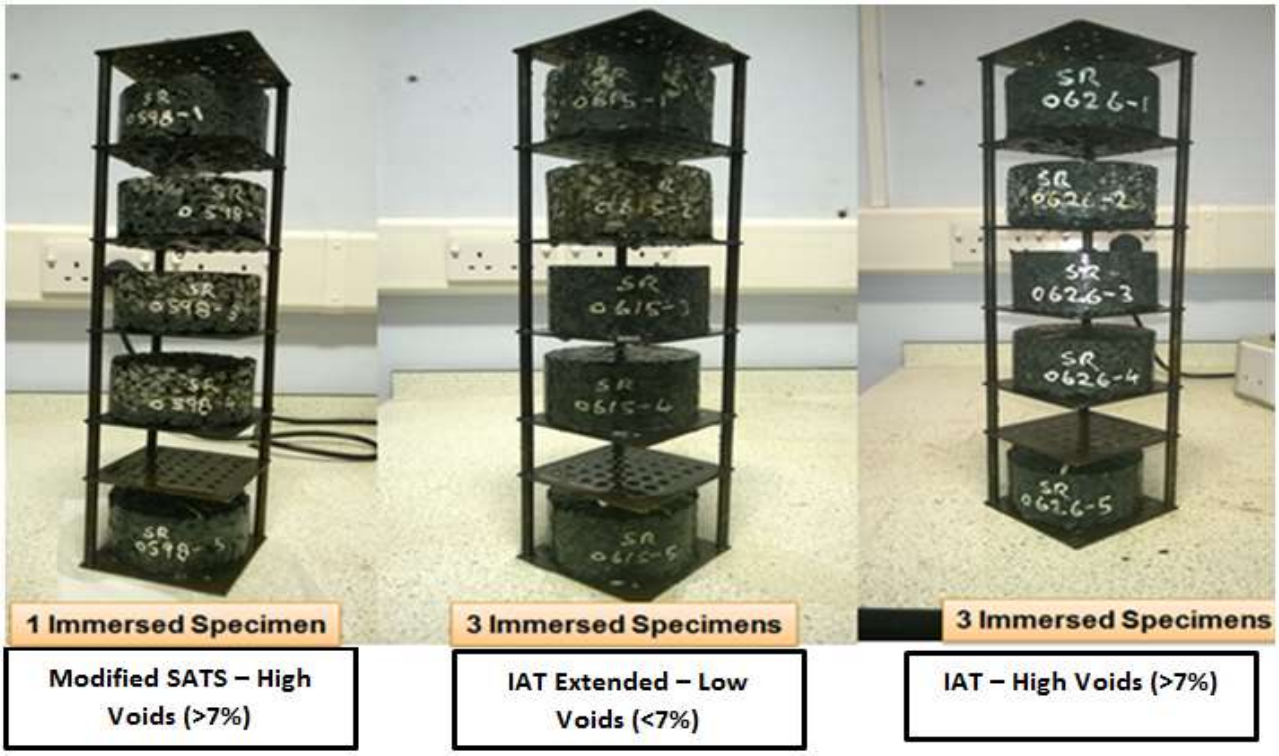


Figure 6-8: Post Conditioning State following IAT Testing

6.2.3 *Binder Rheology using the Dynamic Shear Rheometer (DSR)*

Binder rheology using dynamic shear rheometer (DSR) was conducted on recovered binder from the PMB SMA specimens above water and fully immersed in water in order to ascertain the level of ageing. The samples tested are detailed in Table 6-4 in terms of G* (MPa) at 0.4Hz and 25°C with a calculated penetration value for samples above water and fully immersed in water. The consistency in rheology of samples with PMB's (Sample Numbers: 676, 685 and 686) below water show consistent ageing of the binder with similar ageing to samples above water, which was unexpected (access to oxygen).

Task	Binder	Description	G* (MPa) at 0.4Hz & 25°C	Penetration (dmm) at 25°C
Task 2: PMB - IAT	676-1	PMB C, <7%, Standard Protocol Above Water	0.71	35
	676-4	PMB C, <7%, Standard Protocol Below Water	0.72	35
	685-1	PMB C, <7%, Modified SATS Above Water	0.90	31
	685-4	PMB C, <7%, Modified SATS Below Water	1.13	27
	686-1	PMB C, >7%, Modified SATS Above Water	2.16	19
	686-4	PMB C, >7%, Modified SATS Below Water	0.90	31

Table 6-4: Task 2 IAT Samples Tested for Binder Analysis

6.2.4 *Summary*

The test results show that consistent results for saturation and stiffness ratio may be obtained by the new IAT protocol for immersed samples. Polymer modified SMA suitable for surface courses with low voids may be tested using IAT and interestingly the ageing of recovered binder is equivalent to samples above water.

7 BINDER RECOVERY AND COMPOSITIONAL ANALYSIS

7.1 Introduction

Composition analyses by SARA (Saturates Aromatics Resins Asphaltenes) were conducted to assess the influence of binder recovery methods to the level of maltene phase in the recovered binder. A different extraction method was trialed using n-heptane, which is less aggressive in obtaining the fractional components in comparison to using the dichloromethane (DCM) which is a more polar solvent. The process is detailed in this section. The concept was to extract the lower molecular fraction, which is termed the maltene phase, leaving the higher molecular weight material (asphaltenes) attached to the aggregate. It is the lighter ends (lower molecular fraction) that provide durability in terms of healing and resistance to ageing and cracking. SARA analysis by thin layer chromatography was used (Iatroscan).

The main objective of this analysis was to obtain a better method to assess suitability of reclaimed asphalt binder for potential recycling of TSCS. Ideas to provide a quick analysis of aged material or for reclaimed asphalt were considered.

7.2 Soxhlet Extraction

Soxhlet extraction of the binder using n-heptane as the extraction solvent was conducted. For comparison, dichloromethane (DCM) as the soxhlet extraction solvent was used for one sample. In order to achieve a suitable homogeneous sample for Soxhlet extraction, a representative portion of the core sample was broken in to small fragments as shown in Figure 7-1 below.

Figure 7-1: Example of Broken Core Sample

A known weight of the broken core sample was transferred to an extraction thimble and approximately 2g of anhydrous sodium sulphate was added to the sample thimble and glass wool was placed inside the thimble to prevent loss of sample during extraction. 200ml of extraction solvent (heptane or dichloromethane) was transferred to a round bottom flask into which about 2g of copper granules was added. The extraction thimble was placed into the extractor and the Soxhlet apparatus was assembled, see Figure 7-2.

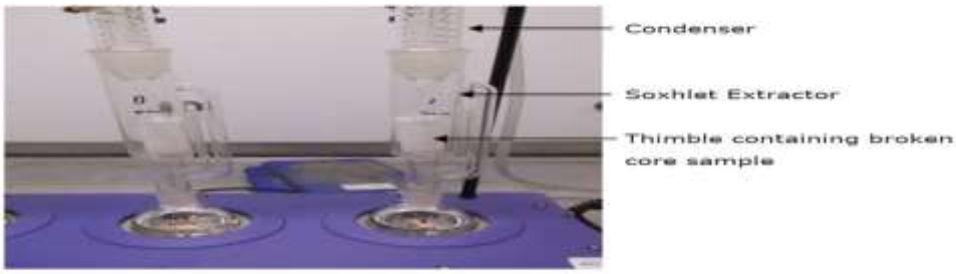


Figure 7-2: Assembled Soxhlet Extraction Apparatus

The heating mantle was switched on and once the solvent started to boil, the sample was continually extracted until the solvent in the extractor was clear. Figure 7-3 shows a comparison of the extracts obtained for samples with n-heptane extract on the left-hand side and the dichloromethane extract on the right-hand side.

Figure 7-3: Comparison of n-Heptane and Dichloromethane Extracts

7.3 Solvent Extractable Matter (SEM)

The concentrated solvent extract obtained from section 7.2 was quantitatively transferred to a pre-weighed 7.5ml glass vial. The round bottom flask was washed with a small volume of solvent and the washings were added to the contents of the glass vial. The vial was placed on a hotplate and the contents were evaporated to dryness under a gentle stream of air from an air pump. When cooled, the vial was re-weighed. The vial was returned to the hotplate and blown with a gentle stream of air for a further 5 minutes. When cooled, the vial was re-weighed. This procedure was repeated until a constant weight was achieved. The SEM (solvent extractable matter) concentration of the core sample was calculated as follows:

$$\text{SEM (mg/kg)} = \frac{(W_2 - W_1) \times 10^6}{W_c}$$

Where:

W_1 – weight of empty vial, g
W_2 – weight of vial + extract, g
W_c – weight of “as received” core sample extracted, g

A summary of the SEM (solvent extractable matter) results obtained for the samples are presented below in Table 7-1.

Core Reference	Weight of “as received” Core (g)	Weight of Extract + Vial (g)	Weight of Vial (g)	Weight of Extract (g)	SEM (mg/kg) “as received”
615-2	5.0	6.8469	6.7013	0.1456	29120
615-5	5.0	6.8630	6.6484	0.2146	42920
616-2	5.0	6.8101	6.6309	0.1792	35840
616-5	5.0	6.8448	6.6791	0.1657	33140
625-2	5.0	6.9025	6.6301	0.2724	54480
625-5	5.0	6.8391	6.6629	0.1762	35240
626-2	5.0	6.8847	6.6218	0.2629	52580
626-5	5.0	6.9388	6.7048	0.2340	46800
615-2 (DCM)	1.0	6.7263	6.6163	0.1100	110000

Table 7-1: SEM (Solvent Extractable Matter) Results Summary

7.4 SARA Analysis by Thin Layer Chromatography – FID (Iatroscan™)

Thin layer chromatography with flame ionization detection (TLCFID – Iatroscan™) was used to classify the extracts into their component classes. A 1% solution of each of the SEM extracts, obtained in section 7.3 was prepared by dissolving a known weight of the extract into a known volume of an organic solvent (heptane or dichloromethane). Using an auto-spotter (Figure 7-4), an aliquot of each extract was spotted onto separate silica rods.

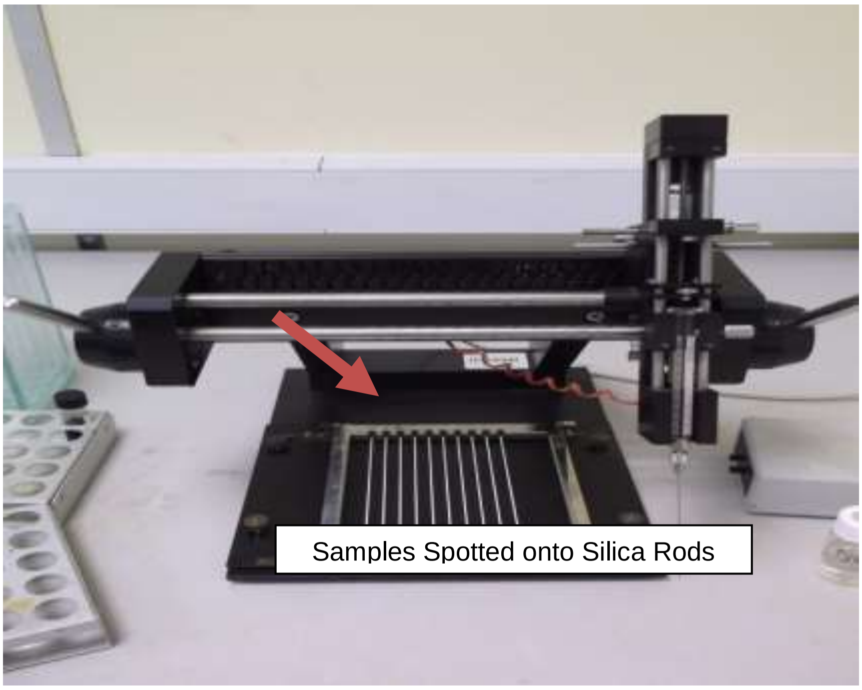


Figure 7-4: SARA Auto Spotter

The rods in batches of 10 were immersed in a development tank containing a non-polar solvent (n-hexane) and by capillary action, the non-polar saturates (aliphatics/mineral oil) traverse up the rods with the solvent. The polar material, which has more affinity for the silica than the solvent, remains at the base of the rod. At a given point the rods were removed and dried. The dried rods were placed in a development tank containing a more polar solvent (20% n-hexane: 80% toluene). The polynuclear aromatics which are mainly polar and having more affinity for the solvents move with the solvent up the column.

Following this, the rods were removed and dried. A similar procedure was used to separate the nitrogen, sulphur and oxygen (NSO)/polar resins and asphaltenes. For this separation, a more polar solvent was used, 95% dichloromethane: 5% methanol in the development tank. The rods were dried and placed on an Iatroscan™ flame ionization scanner (Figure 7-5).

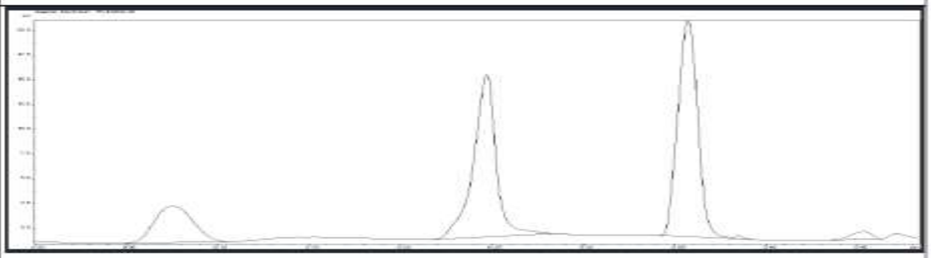
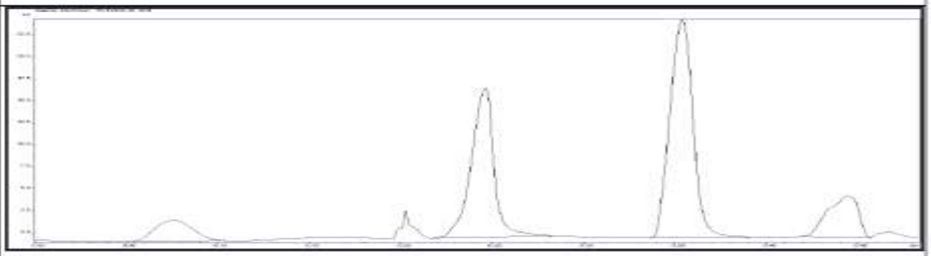
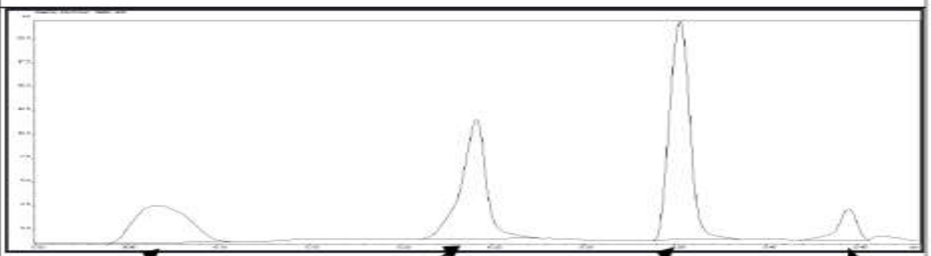
Figure 7-5: Iatroscan™ Flame Ionization Scanner

The percentage of saturates, aromatics, NSO/polar resins and asphaltenes was determined as an area percentage of the chromatogram obtained. The SARA (Saturates, Aromatics, NSO/Polar Resins, and Asphaltenes) analysis results obtained for the core samples are summarised in Table 7-2 below.

Core Reference	Saturates (% weight)	Aromatics (% weight)	NSO/Polar Resins (% weight)	Asphaltenes (% weight)
615-2	14.46	38.67	45.16	1.71
615-5	11.85	31.62	55.05	1.48
616-2	9.55	40.98	47.37	2.10
616-5	10.65	47.62	39.48	2.25
625-2	7.43	34.53	55.97	2.07
625-5	8.33	45.43	44.06	2.18
626-2	6.51	41.35	46.23	5.91
626-5	7.49	44.18	46.82	1.51
615-2 (DCM)	7.44	32.51	48.03	12.02

Table 7-2: SARA Analysis Results - Summary

Figure 7-6 shows a comparison of the SARA chromatograms obtained for the n-heptane and dichloromethane extracts of sample 615-2 in comparison with a SARA chromatogram of an AQC sample (fuel oil). It can be seen that the n-heptane elution resulted in low asphaltene concentration compared to the DCM visibly shown in Figure 7-3 (darker eluate, evidence of larger molecules).

Sample Identification	SARA Chromatogram
15/12304-001 (615-2) n-Heptane Extract	
15/12304-001DCM (615-2) Dichloromethane Extract	
SARA AQC (Fuel Oil)	

Saturates (S) Aromatics (A) NSO/Polar Resins (R) Asphaltenes (A)

Figure 7-6: Example SARA Chromatograms

7.4.1 *Aliphatic/Aromatic Fractionation*

Known weights of the SEM extracts as obtained in section 7.3 were dissolved in a non-polar solvent, n-heptane. The extract solutions were then fractionated into aliphatic and aromatic fractions using the UKAS accredited method described below:

The fractionation into aliphatic and aromatic fractions was accomplished by solid phase column chromatography using silica and alumina. The aliphatic compounds which have no affinity for either the silica or alumina were eluted using n-heptane. The aromatics, remaining on the column after the removal of the aliphatics, have no affinity for either the silica or alumina when eluted using a more polar solvent, dichloromethane (Figure 7-7).

Elution of the aromatics, with dichloromethane, continued until the eluate ran clear. The aromatic fraction was quantitatively transferred to a pre-weighed (to 4 decimal places) 7.5ml glass vial. The contents of the vial were evaporated to dryness under a gentle stream of nitrogen after which the vial was re-weighed. The vial was blown under a gentle stream of nitrogen for a further 5 minutes, after which time the vial was re-weighed. This procedure was repeated until a constant weight was achieved. The weight of the aromatics extracted from each sample was subsequently calculated and are presented in Table 7-3 below.

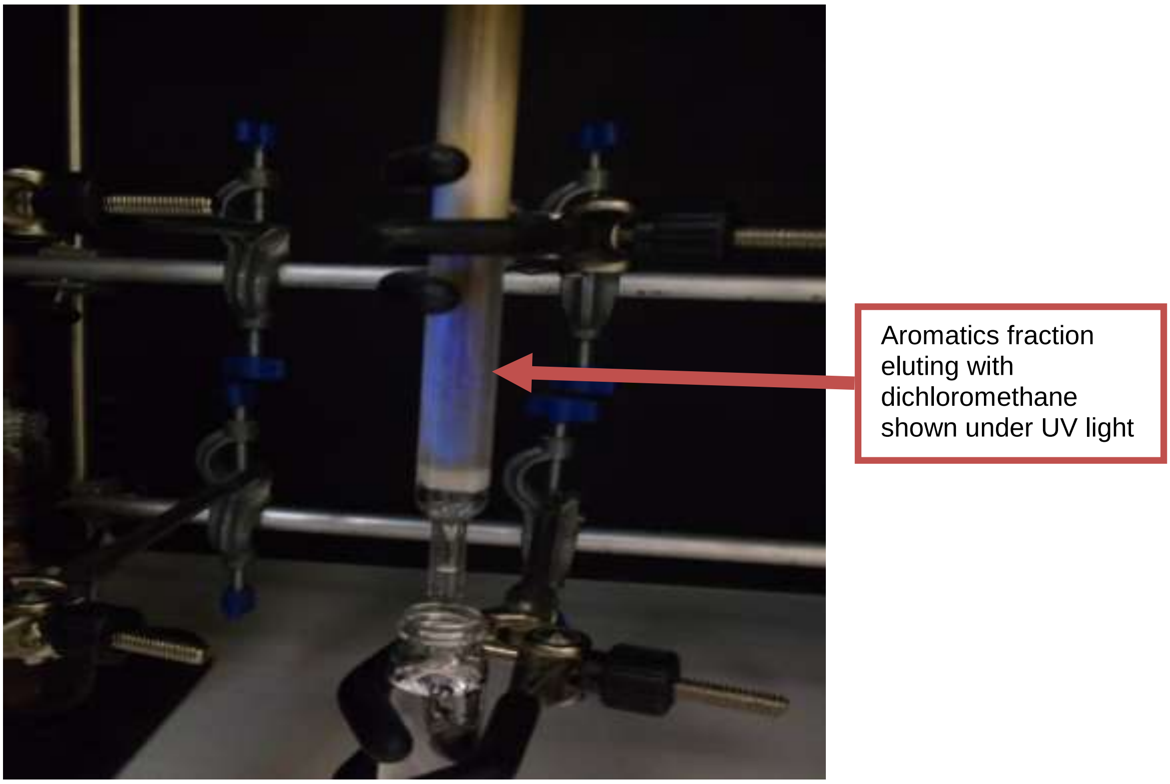


Figure 7-7: Aromatics Eluting under UV Light

Core Reference	Weight of SEM Extract Used (g)	Weight of Aromatics Extract + Vial (g)	Weight of Vial (g)	Weight of Aromatics Extract (g)
615-2	0.0668	6.7068	6.6745	0.0323
615-5	0.0908	6.6911	6.6525	0.0386
616-2	0.0811	6.6431	6.6019	0.0412
616-5	0.0688	6.5877	6.5528	0.0349
625-2	0.1217	6.7161	6.6508	0.0653
625-5	0.0781	6.6814	6.6323	0.0491
626-2	0.1184	6.6756	6.6133	0.0623
626-5	0.1000	6.7149	6.6446	0.0703
615-2 (DCM)	0.0500	6.5773	6.5553	0.0220

Table 7-3: Weight of Aromatic Extracts following Fractionation

7.4.2 *Semi-Volatile Organic Compounds (SVOC) by GCMS*

The aromatic extracts of the core samples obtained in section 7.4.1 were dissolved in an organic solvent and analysed by GCMS for the presence of semi-volatile organic compounds (SVOCs). Prior to GCMS analysis a known volume of a deuterated internal standard solution was introduced into each sample extract. The deuterated compounds used were 1,4-Dichlorobenzene-d4, Naphthalene-d8, Acenaphthene-d10, Phenanthrene-d10, Chrysene-d12 and Perylene-d12. A known volume of the extract was injected by the auto-sampler into the 6890N Gas Chromatograph (Figure 7-8) via a heated injector port and was analysed by temperature programmed capillary gas chromatography. Detection was achieved using a mass selective detector (5975B Inert MSD) which was capable of acquiring selective ion monitoring (SIM) data and Full Scan data simultaneously. The SIM data acquired were used to identify and quantify the 62 USEPA target list of SVOCs.

Figure 7-8: GCMS System used for SVOC Analysis

Identification of the target list SVOCs was initially, carried out by comparing the retention times of the analytes to those of the calibration standards. The mass ion ratio of the analyte was subsequently compared to the mass ion ratio of the particular compound in the calibration standard. For a positive identification to be achieved the mass ion ratio of the analyte should fall within ±20% of that of the compound in the calibration standard. Quantification was carried out by means of the internal standard technique against a 7-point calibration curve for each of the individual target list compounds in which the response of an analyte at different concentrations relative to an internal standard of known concentration was used. The Full Scan data were used to identify and quantify any non-target or tentatively identified compounds (TICs) detected in the sample extract. The mass spectrum of the TIC was compared to a reference library of compound mass spectra contained in the GCMS software. In order for a TIC to be quantified and reported the mass spectrum had to meet or exceed 80% quality match. Quantification was by means of the internal standard technique in which the response of the TIC relative to an internal standard (acenaphthene-d10), of known concentration, was used. Results of the GCMS SVOC chromatograms and the tentatively identified compounds are presented in the appendix.

7.5 Summary

The n-heptane method of extraction providing essentially the maltene phase from an asphalt sample has been demonstrated. Maltene phase is known to have substantial influence to durability (resistance to cracking and healing) of bituminous binder. The new method will allow further testing of the recovered binder (which will be rich in maltenes), to assess its suitability for recycling. The concept is to test this lower molecular weight oily sample using rheology for rapid evaluation and compare this with asphalt performance, rather than the current method considering penetration value of the total binder. This will require greater samples for test and scaling up by using the rotary flask method (BS EN 12697-3) with n-heptane as the solvent. Chromatographic testing of this extract could also be investigated.

8 ASSESSMENT OF GERMAN SMA THIN SURFACE COURSE SYSTEMS

8.1 Introduction

This exercise was conducted in order to assess properties of German SMA's. 3 samples were obtained from a site which was constructed in 2007 (Aged 9 years) using 3 aggregate rock types that included Rhyolite (1.5), Diabase (2.5) and Greywacke (3.5) produced in accordance with ZTV Asphalt – StB 2001.

8.2 Test Results

Typical mix design details are presented below in Table 8-1 while Table 8-2 shows results of the mean texture depth and skid resistance.

Properties	Units	1.5 (Rhyolite)	2.5 (Diabase)	3.5 (Greywacke)
			Mixture	
Sieve Size > 2mm	M.-%	75.1	74.1	74.2
Sieve Size 0.063 - 2mm	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
Degree of Compaction	%	101.3	101.5	100.9
Layer Thickness	cm	4.7	4.7	4.7
			Binder: 25/55-55	

Table 8-1: Composition and Material Properties of the German SMA Samples

Sample Reference	Bulk Density (kg/m^3)	Mean 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

Table 8-2: Mean Density, Texture Depth, PTV and ITSM Test Results

The mixture is made with a high amount of the coarse aggregates with the air voids filled with most part with bituminous mortar. After 9 years in service, the residual air voids seem to vary between 0.4 and 1.2%, which suggested densification would have taken place. However there was no information available on the rutting performance of this material. Furthermore, German SMA has been designed to have relative low initial air voids, specifically: between 2 and 4% (laboratory mix design) and not greater than 6% (in situ).

The recovered binder content of the mixtures ranged between 6.5 to 6.7%, which indicate good and consistent specification and production control between projects (assuming these three samples from three different projects).

The mean texture depth after 9 years exceeded 1mm which indicates good retention in texture after 9 years of trafficking. The variations in texture depth values, between 0.8 and 1.1mm suggest good consistency on surface characteristics of between these three surface courses. Furthermore, these results suggest good surface macrotexture can be achieved even at the relatively residual low air voids (0.4 – 1.2%) in situ.

The pendulum test value after trafficking for 9 years was consistently above 70 indicating good retention on wet skid resistance characteristics.

Stiffness values may not be a primary requirement for thin asphalt surface but it can provide indication on the state of ageing of the material, and the associated risk to durability. The stiffness values ranged between 4000 – 5000 MPa as stated in Table 8-2 seems to be comparable to similar asphalt surfacing materials with good surface condition after a few years in service. This may suggest the German SMA samples have reasonably good resistance to age hardening.

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

Table 8-3: Penetration and Softening Point for the German SMA Samples

Binder composition, penetration and softening point using DSR was carried out on extracts from the German SMA with results shown in Table 8-3. For comparison, a good performing PMB was used; specifically that after RTFOT (SBS 80/60 R) and after HiPAT (SBS 80/60 H). A standard 40/60 pen after HiPAT (40/60 Pen H) is also included in the analysis. The Rolling Thin Film Oven Test (RTFOT) was used to simulate the ageing which occurs during the mixing, transportation and laying processes, whilst The High Pressure Ageing Test (HiPAT) was used to simulate the ageing which occurs in a binder whilst in service. Figure 8-1 displays the black diagram for the samples.

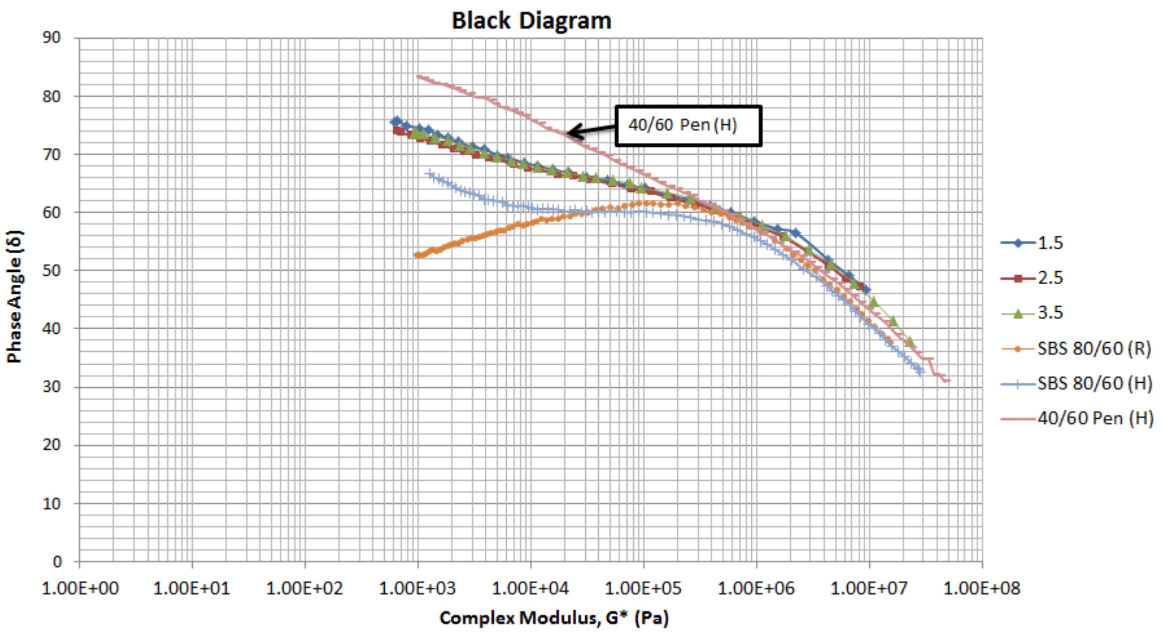


Figure 8-1: Black Diagram for the German SMA Samples

The German SMA samples (1.5, 2.5 and 3.5) showed comparable results in the black diagram, consistent with the results presented in Table 8-3. At lower phase angles, all materials displayed were very similar characteristics. However, as seen in Figure 8-1, a more pronounced difference was observed at higher phase angles with the 40/60 Pen (H) after HIPAT demonstrate the highest phase angle (more viscous response) at G* value near the softening point of the binder, followed by the three German binders and then the reference SBS 80/60 binders.

As expected, the 40/60 Pen (H) demonstrated the highest stiffness (G*) which indicated greater susceptibility to age-hardening in comparison to the PMB's; these trends are illustrated in Figure 8-2. In this chart, the SBS 80/60 H showed some similarities with the German SMA binders on the temperature susceptibility of G* values.

Figure 8-3 showed that the German SMA binders had consistent viscoelastic response over the service temperature range. The 40/60 Pen H 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 more viscous response, suggesting lower resistance to deformation.

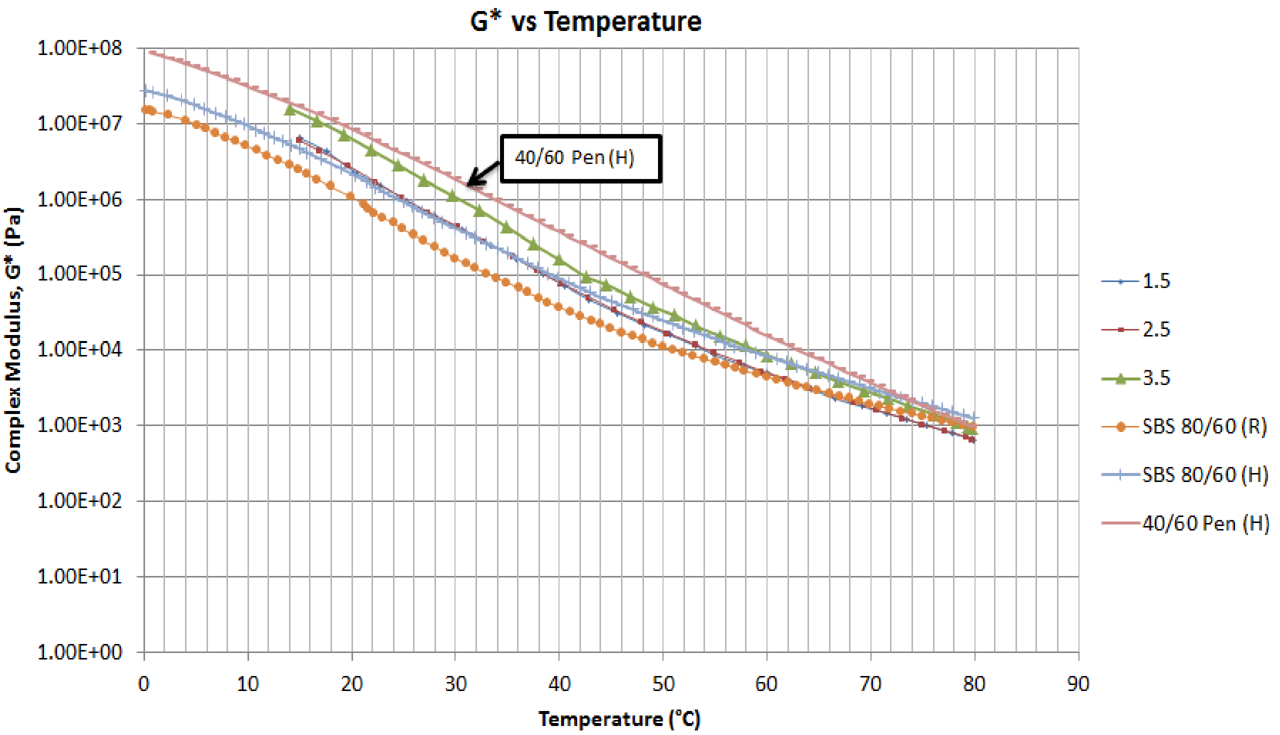


Figure 8-2: G* vs Temperature

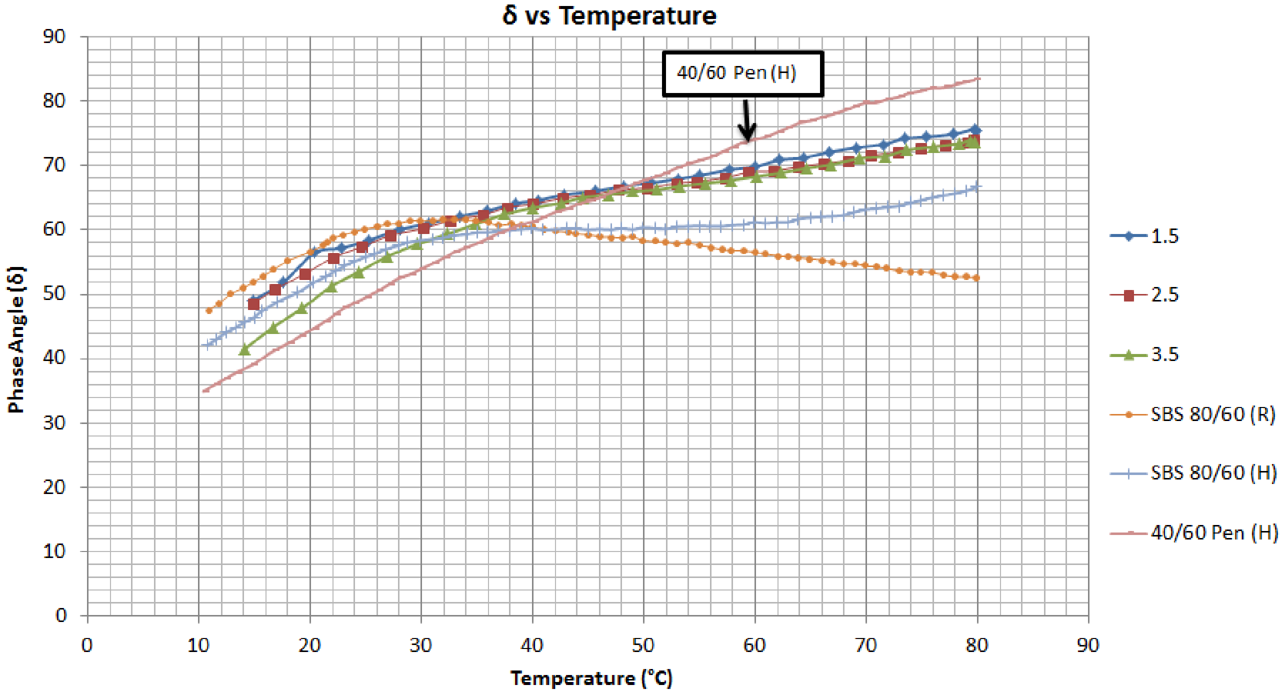


Figure 8-3: δ vs Temperature

8.3 Summary

After 9 years in service, polymer modified thin SMA samples were extracted from motorways in Germany, The recovered binder content, ranged between 6.5 and 6.7%, may indicate good and consistent specification and production control between projects. Stiffness values seem to be comparable to similar asphalt surfacing materials with good surface condition after a few years in service. This may suggest the German SMA samples have reasonably good resistance to age hardening.

Whilst there was no information available on the rutting performance of this material, it was suspected that densification may 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 9 years (the mean texture depth was found to be greater than 1mm which indicates good retention in macrotexture) despite the fact that it had high binder content and low air voids (0.4 to 1.2%). Furthermore, the pendulum test value after trafficking for 9 years was consistently above 70 indicating good retention on wet skid resistance characteristics.

9 THE FUTURE: ACCELERATED PAVEMENT TESTING USING THE MODEL MOBILE LOAD SIMULATOR (MLS)

9.1 Introduction

The MLS system is an Accelerated Pavement Testing (APT) device that applies a scaled load on four single tyres. One of the main advantages of using the MLS system is its ability to vary the test conditions as required and to conduct tests both in the laboratory and on site. A major feature of the MLS range of equipment is the very high number of axle loads that can be applied in a given time. The equipment is manufactured in three major ranges as stated in Table 9-1. As illustrated in this table, all of the MLS test equipment is capable of applying more than 1 million passes of wheel load per week.

	MLS 11 (MMLS3)*	MLS 30	MLS 66
Dimensions (m)	2.7L x 0.7W x 1.2H	11.2L x 2.6W x 3.1H	14.8L x 2.6W x 3.1H
Mass (kg)	700	39,000	46,000
Quantity of Wheel Carriages	4 wheel boogies	4 wheel boogies	6 wheel boogies
Full Load Test Section Length (mm)	1070	3300	6900
Tyre Footprint Length (mm)	1420	4000	7600
Traffic Wheel Width (mm)	80	590 (dual tyres)	
Trafficking Width (Lateral traffic width, mm)	80-230 (0±75 wander)	590-159 (0±500 wander)	
Lateral Traffic Load Distribution	Gaussian or Channelized	Gaussian, Step function, Channelled or any user definable distribution	
Wheel Description and Configuration	Single	Dual/Super Single	
Wheel Suspension and Load Control	Constant Load – Mechanical Spring	Constant Load – Pneumatic Hydraulic	
Tyre Pressure (kPa)	560-800	500-1000	
Wheel Load (kN)	1.9-2.9	10-75	
Wheel Velocity (m/s)	0.5 to 2.5	1.5 to 6	
Nominal Maximum Wheel Passes/hour	7200	6000	
Rut Depth (max, mm)	10	40 with wander, 80 without wander	
Fabrication Unit	Metric system		
***MLS11 was formerly known as MMLS3, a third scale model**			

Table 9-1: MLS Test Equipment Range (PaveTesting, 2016)

Measurements are taken to determine a wide range of performance factors which include structural performance of specific pavement compositions, rutting performance, impact of speed under various loading, environmental and temperature conditions. The MLS has been applied as an accelerated pavement testing system to evaluate a number of characteristics that include as stated by (Hugo et al., 2015):

a) Rutting
b) Moisture damage
c) Fatigue
d) Failure mechanisms
e) Evaluation of pavement structural systems, including geosynthetic reinforcement and bond between layers
f) Pavement surface characterisation
g) Skid resistant

In contrast to empirical tests, the MLS provides a good simulation of the field criteria (Hugo, 2015). Empirical tests are known to provide results that relate only to the specific test conditions and often cannot easily be explored analytically.

A schematic of the MLS is shown in Figure 9-1 while Figure 9-2 depicts a section of the MLS11 equipment.

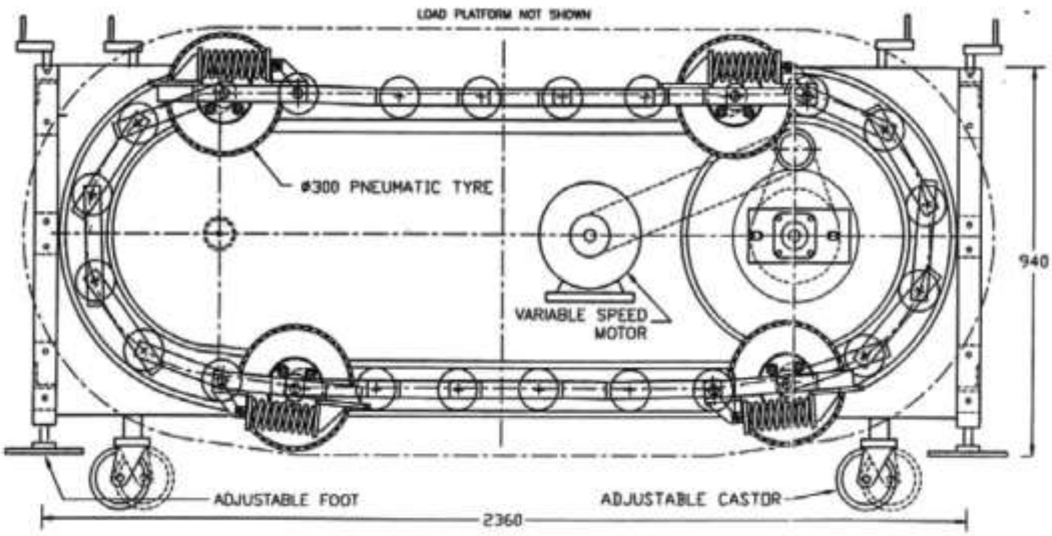


Figure 9-1: Schematic of the MLS

Figure 9-2: Section of the MLS 11

Figure 9-2 shows the cooling/heating unit on the pavement/slab pavement model used to either heat or cool down the pavement or slab for use in both laboratory and field conditions. In order to maintain an even air distribution, the direction of airflow is automatically reversed every few minutes. If required, this can be used in conjunction with the environmental chamber shown in Figure 9-3.

Figure 9-3: Environmental Chamber (Hugo et al., 2005)

SANS (2016) describes a method to measure both deformation performance (rutting) and susceptibility to moisture damage of asphalt concrete mixtures when using a simulated traffic loading (MMLS3). Annex B.2 of the SANS (2016) provide guidelines, that is, an interim protocol for evaluating moisture susceptibility or damage to asphalt concrete pavements. Annex B.3 of the SANS (2016) describes the preparation of specimens and trafficking. Reference should be made to SANS (2016) for detailed information.

MLS has been used to evaluate full-scale pavements, including airports and highways in situ, (Hugo et al, 2011). The MLS system correlates with most APT full scale equipment including the Heavy Vehicle Simulator (HVS) and serves as a useful tool to supplement full scale APT testing. In particular, the MLS30 has been successfully used to evaluate the performance of HMA under moderate climatic conditions and high-speed traffic.

Findings obtained from MMLS studies have contributed to the current SANS (2016). This document has been expanded to include the physical characterizations of asphaltic materials under more extreme conditions such as steep gradients, prolonged high temperatures, very heavy slow traffic and high tyre pressures, moisture ingress and durability related aspects, among others.

In addition to testing on slabs in the laboratory and in the field, tests can be conducted on cylindrical asphalt specimens in the laboratory as depicted in Figure 9-4. Figure 9-5 depicts the use of strain gauges in the pavement slab and typical outputs.

Figure 9-4: Cylindrical Test Bed Accelerated Pavement Testing for the MLS

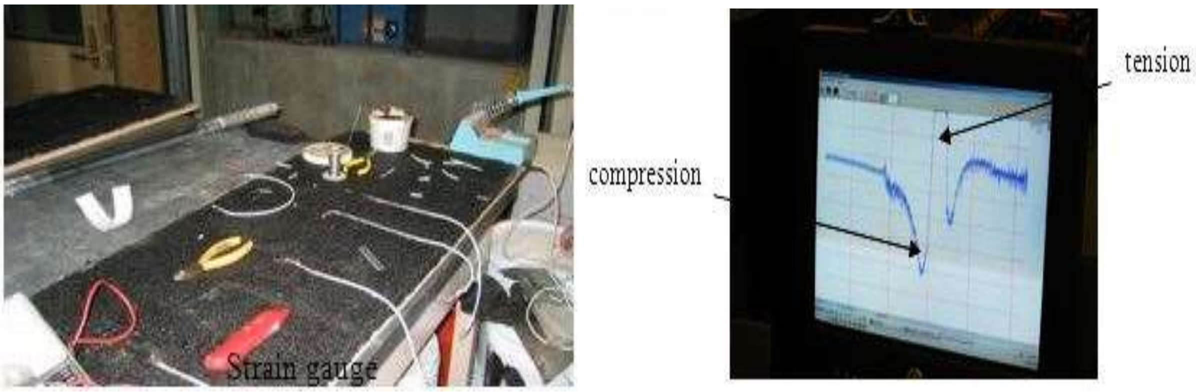


Figure 9-5: Strain Gauges in Pavement Slab

9.2 Visit to EMPA

EMPA is the Swiss research centre of materials for building and construction, situated in Dubendorf, near Zurich. The visit took place on Thursday 8 October 2015, attended by Arash Khojinian (Highways England), Martin Heslop (ACLAND) and Dr. Daru Widyatmoko (AECOM) and was hosted by Andy Treuholz and Dr. Martin Arraigada (EMPA).

There are two variants of MLS equipment at EMPA, specifically the full scale MLS30 and a third scale MMLS3 which were run at their facilities in Dubendorf and Lenzburg respectively.

The visit was started by presentation from Dr Arraigada about their past and current research at EMPA, with specific focus on their experience in utilising MLS accelerated loading equipment. Over the last ten years, EMPA has carried out research on performance and durability of materials for road and bridges using this equipment. These studies include:

- Moisture damage of asphalt surfacing;
- Durability of joint sealants for road bridges;
- Effectiveness of geosynthetics to resist reflection cracking;
- Assessment of fatigue cracking and rutting in pavement;
- Assessment of warm asphalt mixtures.

Amongst the above research themes, most of discussions between EMPA and the UK research team were evolved around the effectiveness of the equipment to assess the durability of thin asphalt surfacing, specifically on their resistance to fretting and moisture related damage. An extract from EMPA works, specifically related to this current research, is reproduced in Figure 9-6.

In the afternoon, the team was taken to EMPA facility at Lenzburg where the full scale MLS30 equipment has been kept and operational. The MLS30 test equipment is depicted in Figure 9-7.

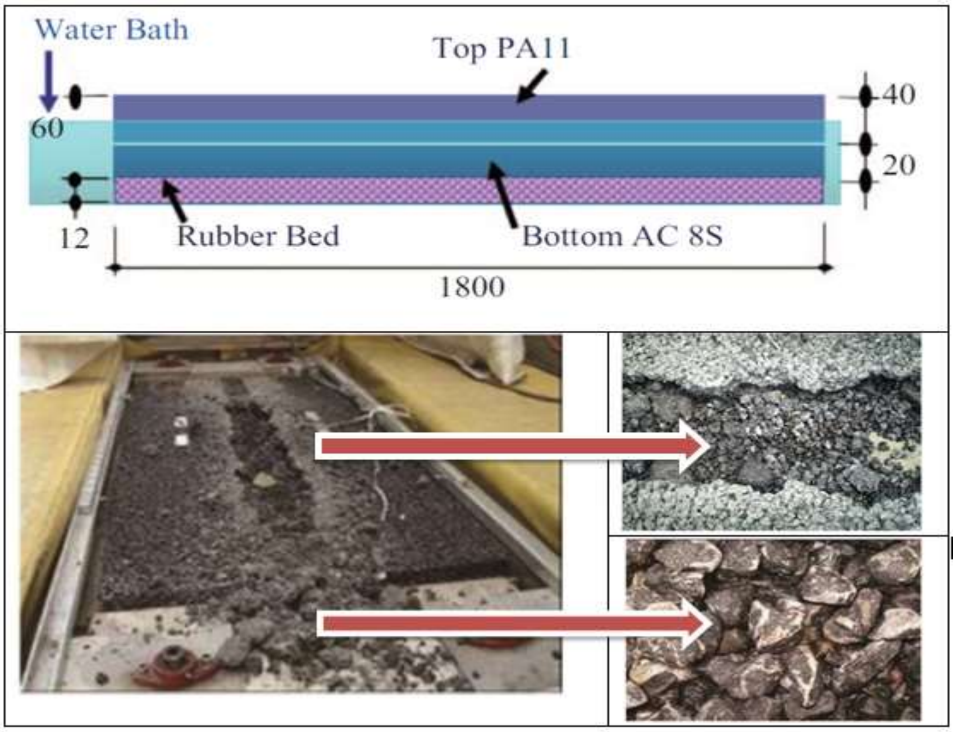


Figure 9-6: Stripping of Porous Asphalt Tested with MMLS3 (Partl et al, 2015 and Raab et al, 2012)

Figure 9-7: MLS 30 Test Equipment

9.3 Visit to PaveTesting

PaveTesting are the registered owners of the MLS Test Systems. Currently, manufacturing of the MLS suite of equipment is in South Africa in the short term after which manufacturing will be transferred to the UK. The visit took place on Tuesday 9 February 2016, attended by Arash Khojinian (Highways England), Martin Heslop (ACLAND), Daru Widyatmoko (AECOM) and Chibuzor Ojum (AECOM) hosted by Barry Goff and Gareth Saynor (PaveTesting) at PaveTesting Head Office in Letchworth, Hertfordshire.

Barry Goff started the presentation by introducing the company and the range of products available. PaveTesting produces test equipment that includes equipment for:

- Deflection Testing
- Laser Profilometer
- Friction Testing
- Accelerated Pavement Testers

Site visit round the office was conducted. The 1/3rd Scale, MLS 11 as depicted in Figure 9-8 was trialed and demonstration of its functionalities shown.

Figure 9-8: MLS 11 Located at PaveTesting Office

Following this, the presentation continued with details of the MLS 30 and 66 discussed.

9.4 Relevant Case Studies

A literature review was conducted relevant case studies are detailed below:

9.4.1 *Impact of Moisture Related Damage and Pavement Performance – USA and Switzerland*

The study entailed field trafficking under wet conditions using the MMLS with lateral wander (to simulate traffic-patterns) with a purpose to evaluate stripping distress (overall effect of moisture under repeated loading – fatigue) and the performance of the pavement structure. Study findings revealed that

- Under wet conditions, MMLS3 trafficking of a highway pavement (in situ) provided physical evidence of stripping distress. By using the spectral analysis of surface waves (SASW), it was also confirmed that there was a reduction in the Young's modulus of the asphalt concrete surfacing of the pavement after 1.45 million MMLS3 load applications. Under dry condition, trafficking of the same pavement with 1.0 million load applications resulted in a rut depth of 1.8 ± 0.2 mm.
- Extensive field testing with the MMLS3 on selected sections of the National Centre for Asphalt Technology (NCAT) test track provided evidence of increased distress of the asphalt concrete layer owing to wet condition and MMLS3 trafficking with lateral wander. Of interest, the asphalt concrete cores that were extracted after a wet MMLS3 test, fractured.
- MMLS3 tests on 48 cores from different regions and pavements in Switzerland provided evidence of variations on the effect of wet testing. Overall results showed that wet testing increases the potential for distress, (Hugo et al., 2015).
- The use of repeated load applications and wet trafficking that was purposed for evaluating moisture damage while using the MMLS3 provided supplementary insights to the usually conducted/observed laboratory tests. Following the MMLS3 testing, a reduction in tensile strength as a quantification of distress owing to wet trafficking (specifically, moisture ingress) was verified by comparing the wet trafficked samples to their equivalent mix type trafficked under dry conditions, (Hugo et al., 2015).

9.4.2 *Virginia Centre for Transportation Innovation and Research:*

The MMLS3 was considered in developing a test protocol to evaluate the polishing of asphalt concrete specimens that were prepared in the laboratory. Findings revealed that:

- The MMLS3 is capable of applying realistic rolling wheel-contact stresses similar to those experienced on the highways, (Druta et al., 2014)
- The MMLS3 can be used to simulate traffic wearing of asphalt concrete specimens of different shapes and sizes in the laboratory, including core specimens removed from existing pavements, (Druta et al., 2014)
- In terms of skid resistance, friction and texture of actual pavement surfaces and laboratory-fabricated specimens (measured using the British pendulum tester - BPT after different polishing intervals), revealed that the BPT is effective in characterizing changes in friction on specimens that are subjected to simulated trafficking using the MMLS3, (Druta et al., 2014). This finding suggests that with additional instrumentation (preferably well-calibrated) further data and analyses with the MMLS could be attained.

9.4.3 *TxMLS versus MMLS3*

The MMLS3 tests were conducted on the pavement adjacent to the Texas Mobile Load Simulator (TxMLS) with a sheet of water flowing over the surface during trafficking. The findings revealed a significant drop in modulus of elasticity measured by spectral analysis of surface waves (SASW) owing to wet trafficking (presence of moisture). This was in contrast to an increase in SASW modulus of elasticity because of trafficking under warm conditions (38°C). It was also deduced that there was a significant reduction in the indirect tensile and fatigue life of the wet trafficked asphalt. These outcomes were more attributed to micro-fracturing, which showed that the test under the TxMLS that had been trafficked dry was less severe than the test with the scaled device, (NCHRP, 2004).

9.4.4 *N3 Marianhill – South Africa*

N3 is the primary route between Durban and Gauteng. Rutting and fatigue resistance properties were of concern. Due to this, a unique asphalt concrete mix type had to be rut resistant with appropriate fatigue resistance properties. A comprehensive asphalt mix design process allied with performance prediction criteria was considered as key to validating the required mix type and quality.

The design challenge demanded an asphalt mix concrete that exhibits rutting and fatigue resistance properties to withstand heavy trafficking. The MMLS was considered to select an appropriate asphalt concrete mix with either A-P1 or A-E2. The final asphalt concrete mix was based on the proposed limits as set in the Draft Protocol (2008). Specific findings included:

- Dry MMLS tests at 60˚C and 7200 axles/hr (standard speed) were performed on the 4.2 % and 4.5 % A-P1 mix as well as the 4.3 % and 4.5 % A-E2 mix. However, in order to assess the effect of slow loading conditions, MMLS tests were conducted on mix type with 4.2% A-P1 and 4.3% A-E2 at 2400 axles/hr as per Draft Protocol (2008) guidelines.
- Wet MMLS tests were also performed on the 4.2% A-P1 and 4.3% A-E2 mixes using the slow speed 2,400 repetitions per hour to determine moisture susceptibility and potential for stripping of the mixes.

Findings from this study as listed below provided a strong basis for evaluating performance under harsh conditions using the Draft Protocol (2008) guidelines. The following summarises the relevant findings:

- On completion under the dry condition, MMLS test at 2400 axles/hr showed that mix type with A-P1 binder had a terminal rut of 1.66 mm after 100,000 repetitions. Under similar conditions, asphalt concrete mix type with A-E2 binder had a rut depth of about 2.49 mm after 100,000 repetitions; this is 50% more than that registered by A-P1.

- Under wet conditions and after 100,000 repetitions of MMLS trafficking at 2400 axles/hr on asphalt concrete with A-P1 mix, there was a 1.81 mm and no signs of stripping; stripping was assessed visually. Under similar wet conditions, the rut depth after 100,000 repetitions on the mix type with A-E2 binder was 3.21 mm and early signs of stripping were observed at the end of the test. Overall, the A-P1 binder exhibited better performance than the A-E2 mix. Asphalt concrete mix with A-P1 binder registered lower overall rutting resistance; this value was also below the maximum threshold of 2.5 mm after 100,000 load applications as stipulated in Draft Protocol DPG1 (2008).

Based on the MMLS test data and fatigue test data from the 4-point bending beam apparatus, asphalt concrete mix with the A-P1 binder was selected. Findings from this study formed a basis for adjudicating the Draft Protocol DPG1 (2008) guidelines. This study provided insights that enhanced the ability of pavement engineers to improve the performance of asphalt pavement layers.

9.4.5 *Hex River N1 – South Africa (Rutting Investigations)*

Hex River N1 is located in the valley with steep gradients and experiences high temperatures. Due to several failures that manifested including rutting, an in depth study was commissioned to investigate the probable causes of pavement failures. Using the guidelines of the Baton Rouge Protocol, an assessment of the pavement rutting was conducted. Testing was conducted under severe heavy duty traffic conditions at slow moving speed of less than 5 km/hr, steep gradient of 6% and high temperature less than 60˚C. The pavement comprised of a 40 mm asphalt overlay. The following summarises the study:

- The continuously graded asphalt concrete with 60/70 pen binder – after one year of traffic, the 4 km of slow uphill lane exhibited fattening and deformation failures, i.e. over 50% of the total length of the section had failed. The specific failures ranged in severity from mild fattening to excessive deformation (i.e. more than 10 mm).

- An extensive and detailed diagnostic study using MMLS and related instrumentation was carried out to determine the possible causes. The major findings showed that the cause could be attributed to several factors including high temperature, steep gradients and heavy traffic. Other factors of influence included contamination by migrating material-fines, grading specification tolerances and rich binder applications, (Hugo et al, 2011).

Lessons from the Hex River N1 study contributed to the specific test parameters when using the MMLS3:

- At lower trafficking (1800 axles/hr to 2400 axles/hr) a specification of 1.8 to 2.0 mm maximum rutting is recommended than that specified for 7200 axles/hr (standard axles/hr).
- In terms of material suitability, use of high EVA modification or other plastomer would improve the mix quality and performance criteria. The performance of replacement mixes (high modified binder specifically, 5.5% EVA with 60/70 pen binder) registered a satisfactory mix performance.

9.4.6 *Validating the Structural Design (Global Review):*

MMLS has been instrumental in validating and refining the structural design guidelines in a number of countries. Improvements in structural design have been brought about by the insight gained from several MMLS related testing and analysis. Factors of influence on the performance and durability of the pavement structure include:

- Influence of water on the pavement performance and related failure mechanisms,
- Importance of bonding between layers and the quantification of the bonding effect,
- Interaction between structural composition and material characteristics,
- Influence of concrete slab configuration, and
- Influence of support under concrete slabs

Hugo et al. (1999c) reported on the TxMLS tests completed in Victoria, Texas. The testing aimed at evaluating the widely used district pavement design using local siliceous river gravel flex-base with thin asphalt surfacing.

Findings revealed that high construction variability and high asphalt void content led to early fatigue failure of the asphalt concrete layer in the test sections. Trafficking with the TxMLS revealed that deep-seated variability in the pavement foundation allied with ‘lenses of poor materials’ affected the pavement surface profiles.

Following these findings, amendments to the district pavement design, including the structural parameter were made. The traditional construction approach was changed as results revealed that stabilizing the subgrade layers enhanced the structural capacity of the pavement structure.

Additionally, the analysis following MLS test data conducted in South Africa (Hugo et al. 1997) reported that the damage exponent in terms of rutting of a pavement comprising 75 mm of asphalt concrete on a 150-mm cement-treated gravel base course is as high as 7.

Another project conducted at Virginia Tech (VT) assessed the fatigue performance of Warm Mix Asphalt (WMA) prepared with foamed PG-64-22. MMLS testing was conducted at 20˚C on 50-mm asphalt concrete layers.

Fatigue performances were compared in terms of cracking, strain and concurrent portable seismic pavement analyser (PSPA) seismic stiffness. Initial findings passed tests of reasonableness with due regard to comparisons of the respective two structural systems and appropriate levels of intrinsic material characteristics and pavement performance.

The Mozambique field studies (Hugo et al., 2011): The main objective of the study was to develop guidelines for mechanistic-empirical pavement design method for cement stabilized sand bases. Test results showed a good comparison of scale and full-scale pavements relative to the respective wheel loads and number of load applications in terms of:

- Stiffness trends as measured using a PSPA
- Distress mechanisms and surface deformation

Two unique failure mechanisms were identified in the Mozambique study:

- The horizontal shear within the cement-stabilised base layer
- de-bonding at the interface between asphalt surfacing and stabilised layer

Note: The results from this study also evidence that various applications could be attained if the MMLS3 is equipped with ancillary instrumentation and devices. The MMLS is a valuable tool for investigating the structural response of the pavement system.

9.4.7 *Environmental Effects and Material Response:*

Epps et al. (2001) considered the effect of aging and the investigation made use of the MMLS3 at Wes Track study. In another related study, artificial accelerated aging was used to simulate the natural aging of asphalt in APT studies (Hugo et al. 1987; Van der Merwe et al. 1992). Findings from both studies reveal that rutting reduces because of the hardening (stiffening) of the binder due to aging effects, (NCHRP, 2004).

9.4.8 *Accelerated Load Testing of Asphalt Mix Designs for Heavy Duty Pavements (MMLS3) (Emery et al., 2008):*

The Dubai airport asphalt was tested for a range of mix designs and binder types using the MMLS3. Testing was optimised for stripping resistance rather than rutting. The surface layer consisted of two grading – a coarse grading for the runway with increased macrotexture for skid resistance and a fine grading for the taxiways.

The MMLS was used to evaluate the material design changes on a performance basis. Sample cores were tested using the MMLS. Test temperature of 65˚C was based on the expected Dubai temperature range. Two test speeds were selected; 7200 load applications/hour (50kph) and 1800 load applications/hour (12.5kph). MMLS testing showed differences and the effect of binder type on the performance of the asphalt concrete mix under heavy duty trafficking. The MMLS testing provided additional insights into the performance of the asphalt concrete mix.

9.5 Summary

The MLS suite of equipment has a lot of positives as a test method for thin surfacings as it is able to realistically simulate road trafficking conditions coupled with the fact that tests can be carried out both in laboratory and field conditions. Measurements are taken to a wide range of performance factors as detailed in this section of the report.

In this context, MLS11 has been identified as suitable test method which can provide simulative assessment of asphalt materials under controlled conditions in the laboratory or on site. This equipment has been used by research centres in the US, Europe, China and South Africa and was considered to have capability to assess a wide range of material performance including structural performance of specific pavement compositions, rutting performance, impact of speed under various loading, environmental and temperature conditions. The presented case studies demonstrated the suitability of this equipment to enable simulative assessment of durability on thin asphalt layers, and therefore it is recommended that the next phase of the study should include trials of thin surface course system under accelerated loading and different moisture condition, using MLS11 equipment.

10 CONCLUSIONS AND RECOMMENDATIONS

A suite of research programme comprising literature review, study visits and laboratory testing was carried out as part of the study to explore simulative laboratory ageing testing method for thin asphalt surfacing.

The literature review presented different approaches to assess durability of asphalt materials but they were mostly aiming to address the complex interaction between aggregate and bitumen using fundamental, empirical or simulative type of testing arrangements. Most of mix design processes and specifications have been focussing on either empirical or fundamental tests in optimising the design and it was identified that there is a lack of simulative testing adopted in the design process. Consequently a number of approaches have been considered:

- Assessment of test method which can explain the complex interaction between aggregate and bitumen under age-hardening and moisture condition;
- Identifying suitable test method which can provide simulative assessment of asphalt materials in laboratory and in the field.

For the former, a suite of testing was selected, specifically:

- Immersed Ageing Test (IAT) Protocol
- Rheological testing of binders recovered from samples after being subjected to IAT protocol;
- Composition analysis of aged binders using SARA analysis under different binder extraction process;
- Assessment of SMA samples extracted from motorways in Germany.

The IAT assessments concluded with the following findings:

- Binder rich asphalt samples such as TSCS SMA did not show any reduction in the stiffness values after being subjected to IAT conditioning.
- TSCS SMA 10 Surf 40/60 and SMA 10 Surf PMB with low voids can be tested using IAT and immersed samples have consistent saturation and stiffness ratios.
- Results from IAT testing demonstrated improvements in the retained stiffness of TSCS SMA Samples with polymer modified binder over those with standard 40/60pen bitumen. This suggests the benefit of using polymer modified binder in improving resistance to age and moisture damage. These findings were also confirmed by the rheology of binders recovered from these samples.
- TSCS SMA showed equivalent ageing for immersed samples, which is capable of producing more consistent results.
- Only limited number of sample sets have been tested, therefore more work is recommended to account for contributions of aggregate types and/or binder grades.
- The recent developments of the MIST apparatus in the USA would indicate that the IAT immersed samples testing which is similar is worth pursuing. The interesting use of pressure pulsing in the MIST apparatus to simulate traffic damage could be replicated in the IAT protocol without much development of the IAT equipment. The advantage of the IAT is that it is also an ageing protocol.

Assessment of SMA samples extracted from motorways in Germany after 9 years in service presented the following findings:

- After 9 years in service, Densification may have had taken place as shown by the residual air voids between 0.4 and 1.2%. However there was no information available on the rutting performance of this material.
- The recovered binder content, ranged between 6.5 and 6.7%, may indicate good and consistent specification and production control between projects.
- The mean texture depth after 9 years was greater than 1mm which indicates good retention in macrotexture after 9 years of trafficking.

- This polymer modified thin SMA maintained good surface macrotexture for 9 years despite the fact that it had high binder content and low air voids (0.4 to 1.2%) in situ.
- The pendulum test value after trafficking for 9 years was consistently above 70 indicating good retention on wet skid resistance characteristics.
- Stiffness values seem to be comparable to similar asphalt surfacing materials with good surface condition after a few years in service. This may suggest the German SMA samples have reasonably good resistance to age hardening

Binder Recovery and Compositional Analysis

- A new method of binder recovery substituting dichloromethane (DCM) with n-heptane as a solvent has been tested.
- The concept is to consider only the maltene phase, containing the binder fraction that contributes most to healing and resistance to ageing, which affects the durability of asphalt.
- The results show that the test is feasible although to improve repeatability larger samples are required for a quick test using rheology. This may be accomplished by using the standard test BS EN 12697-3 (rotating flask method) and substituting DCM with n-heptane and changing the temperature.
- Further work is therefore recommended to account for larger sample size and subsequent rheological assessment as stated above. Using the Iatroscan and chromatography may provide further information about the capacity for ageing and could be used to evaluate TSCS reclaimed asphalt.

The Mobile Loading Simulator MLS11

- The Mobile Loading Simulator MLS11 has been identified as suitable test method which can provide simulative assessment of asphalt materials under controlled conditions in the laboratory or on site.
- The MLS11 has gone through stages as prototypes and has now developed into a properly engineered machine that has been used in many parts of the world.
- This equipment has been used by research centres in the US, Europe, China and South Africa and was considered to have capability to assess a wide range of material performance including structural performance of specific pavement compositions, rutting performance, impact of speed under various loading, environmental and temperature conditions.
- It may be used to evaluate the performance of geosynthetics as stress absorbing interlayers in a short time.
- The presented case studies demonstrated the suitability of this equipment to enable simulative assessment of durability on thin asphalt layers, and therefore it is recommended that the next phase of the study should include trials of thin surface course systems (TSCS) under accelerated loading and different moisture condition, using MLS11 equipment.

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