URS

Effectiveness of Preservatives on Asphalt Mixtures Project Report

December 2013

DE11/4671–Order No. 22

HAC 560 (1308) MOTT

Prepared for:
ADEPT, DIO and HA

UNITED
KINGDOM &
IRELAND

REVISION SCHEDULE

Rev	Date	Details	Prepared by	Reviewed by	Approved by
1	March 2012	Draft Report for comments	I Widyatmoko Associate	M Heslop Acland	
2	July 2013	Draft Report for comments	C Hill Principal Engineer	I Widyatmoko Technical Director	
3	November 2013	Final Report	C Hill Principal Engineer	I Widyatmoko Technical Director M Heslop Acland	I Widyatmoko Technical Director
4	December 2013	Final Report	C Hill Principal Engineer	I Widyatmoko Technical Director M Heslop Acland	I Widyatmoko Technical Director

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1 INTRODUCTION

1.1 Background

Asphalt preservatives are claimed to extend the life of road and airfield pavement surfacing. They have been used by Local Authorities (Association of Directors of Environment, Economy, Planning and Transport (ADEPT)), the Defence Infrastructure Organisation (DIO, formerly known as Defence Estates) and the Highways Agency (HA), but their level of effectiveness is largely anecdotal.

An earlier study on Effectiveness of Asphalt Preservatives, completed in 2010 under the HA Services Framework Contract 114/2/1308, Task Reference 395 (1308) MOTT, targeted on characterising binders used in a range of asphalt preservatives, before and after ageing. The study demonstrated that these products have the potential to provide benefit in the medium term and, in some cases, in the long term. However, it was recognised that the potential shown from this work, based on binder testing, needed to be extended to include work on asphalt mixtures in service, in particular so that guidance and specification criteria could be developed for these materials.

The ADEPT, DIO and HA all stand to benefit from the application of asphalt preservatives on their asphalt pavements if the efficacy and cost effectiveness of these products can be demonstrated. Subsequently a collaborative project was commissioned under two framework agreements, specifically DE11/4671 Order Number 22 and HAC Task 560 (1308) MOTT. These frameworks have been managed by URS and Mott MacDonald, respectively, and this particular task was carried out jointly by URS and Acland.

1.2 Scope of Work

The current work included a comparative study under laboratory conditions of the effectiveness of asphalt preservatives by taking into account findings from the previous study to encompass issues associated with defects on asphalt mixture surfacing within the road network managed by HA and ADEPT and DIO’s airfield pavements.

Tests on asphalt mixtures, specifically on cores recovered from the network and/or aircraft pavement construction have been carried out, aiming to deliver the following objectives:

Sub-task 1: Developing a test for obtaining an asphalt sample and determination of rheology of recovered binder, to classify the material and assess its suitability for treatment using the ageing protocol from the previous project.

Sub-task 2: Determination of freeze-thaw, fretting potential and permeability on the treated and untreated running surface of the asphalt surfacing material.

2 SUB-TASK 1: DEVELOPING SAMPLING PROTOCOL

2.1 Methodology

Sub-task 1 investigated the measurable changes that take place to naturally aged asphalt and thin surfacing samples with the application of asphalt preservatives and compare the effectiveness of asphalt preservatives on these samples against those of artificially aged binders. The main aim for this sub-task was to develop a protocol to obtain representative sample from the very thin surface of asphalt surfacing (say, the upper 3-5mm of the surfacing). This very thin surface was considered by many asphalt preservative suppliers to be the effective penetrable depth of the preservative where interaction between the existing surface and the applied preservative takes place.

The current practice involves removal of samples from an existing surfacing by coring, followed by binder recovery from the core. Since preservative treatment is normally considered as affecting the upper 3-5mm of the surfacing, this approach involves trimming the upper part of the surfacing layer of the core for use for binder recovery. The recovered binder is subsequently subjected to further testing.
The weakness in this approach is that it is impossible to obtain consistent samples for binder testing, because:

- Accurate removal of 5mm of material from the top of an aged asphalt core is difficult to achieve and varying sample size affects binder recovery.
- Macrotexture and voids are very variable in this thin slice.
- Interaction is variable depending on the penetration of the preservative into the asphalt, the maximum concentration being at the surface.
- The asphalt sample for binder recovery is small and sample area is small, so many cores are needed.

Coring is destructive testing, causing disruption to the road user and weakening the pavement.

An idea proposed by Martin Heslop was to investigate the use of high pressure water jetting retexturing equipment to see if these machines could be modified to collect surface samples for test. This idea was found to be novel; no laboratory had ever examined the solids removed from an asphalt surface using such a process. It was necessary to determine whether there would be sufficient binder available for test.

Other retexturing devices were considered including: bush hammering; shot blasting; and grinding.

High pressure water jetting has advantage in that large samples of the very top surface are collected in a tank in a reasonable time (50m^2/min).

Sampling the top few millimetres over a much larger surface area than coring could achieve and being non-destructive were considered major benefits.

Foster Contracting Limited (FCL) were contacted and agreed to provide road samples for test and modify their machine for trials at an airfield.

Figure 1 illustrates the appearance of surface course before and after the high pressure water retexturing process. The machine is used to improve the skidding resistance of roads by removing excess binder/mortar. The water jets abrade the surface and slurry is produced that is collected in a large vacuum tank by a suction process. The slurry separates out in the tank and water can be removed to reveal a solids sample for test. The feasibility of obtaining sufficient amount of solid containing bituminous material during a single retexturing process was investigated in this sub-task. The solids samples were subsequently subjected to binder recovery and rheological techniques were adopted to assess properties of the recovered binder.

Figure 1: Appearance of surface course, before and after retexturing (reproduced from FCL retexturing brochure)

2.2 Field Trials

Two trials were carried out on a road (B194 Crooked Mile, Essex) and an airfield (RAF Wittering Taxiway) surfacing respectively. The trials comprised retexturing work performed by Foster Contracting Limited using their high pressure water jetting machine which has controls to vary the abrasion in terms of pressure and speed and is capable of removing loose particles and excess bitumen/mortar without inducing any real damage to the surface course. Details of the two trials are presented in Sections 2.3 and 2.4 hereafter.

2.3 B194 Crooked Mile

Retexturing of an old thin surfacing on B194 Crooked Mile, Waltham Abbey in Essex was carried out on 16 December 2011. The surfacing material was reported to be around 8 years old (laid in 2003). It is understood that this proprietary material belongs to the family Stone Mastic Asphalt (SMA) incorporating cellulose fibre and 40/60 grade paving bitumen.

Approximately 2,000 kg of solids were collected from this work; around 100 kg of solids reserved for this study and a 5 kg sub-sample subjected to a further assessment. The appearance of the solids material at the bottom of the storage tank is presented in Figure 2.

Appearance of solid material at the bottom of storage tank

Sub-sample of solid material

Fine aggregate recovered from the solid material

Figure 2: Visual appearance of solid part of the slurry

The solid material can be easily removed by hand, had dry appearance and an odour similar to that of burnt coke and rubber.

Subsequently, the following suite of testing was proposed for the solid part of the slurry:

- Recovery of binder to BS EN 12697-3 [1];
- Rheology by Dynamic Shear Rheometer (DSR) to BS EN 14770 [2];
- Needle penetration at 25^{o}C to BS EN 1426 [3].

Following binder recovery, the weight of the recovered fine aggregate and binder was determined. It was found that the proportion of the recovered binder was 5.3% of the total weight of the solids (i.e. the combined weight of the recovered fine aggregate and binder). The recovered penetration value was found to be 13 d_{mm} and 12 d_{mm} when measured by needle penetration and calculated from DSR data respectively. The rheological properties are presented in Figure 3.

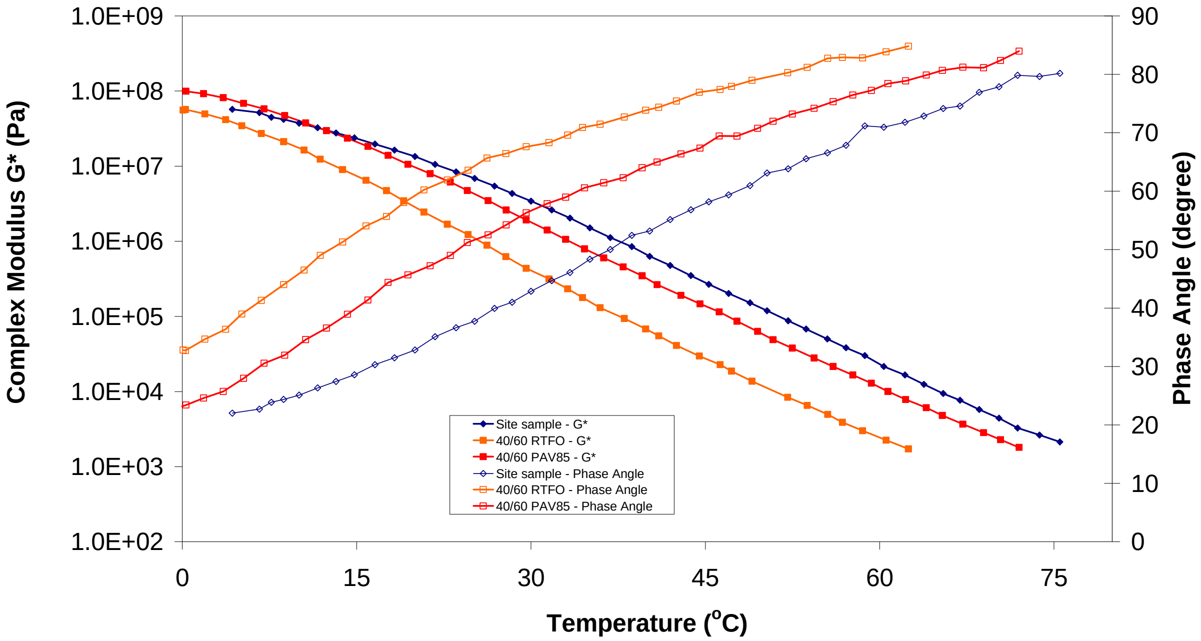

Figure 3: Rheology of binder recovered from the solid part of the slurry

Results from typical 40/60 pen bitumen tested after Rolling Thin Film Oven (RTFO) [4] and PAV85 [5] were also presented in the above figure for comparison purposes. These tests have been used to simulate ageing of bitumen during construction and after 5-10 years in service under UK conditions, respectively.

The rheology test results for the recovered binders suggest significant hardening, which may be considered being more severe than that typically expected for aged surfacing material after 5-10 years in service. The potential presence of rubber components traces from vehicle tyres (which may have been trapped within the macrotexture of the surfacing) which may have contributed to the increased hardness (stiffness) of the recovered binder was assessed. Therefore, transmission infra-red scan spectroscopy assessment was carried out in order to identify any presence of rubber or its constituents (such as Styrene-Butadiene-Styrene, SBS or Styrene-Isoprene-Styrene, SIS polymers). The study was carried out on the solids sample and binder recovered from that sample. The findings were unexpected because they reported that there was no evidence of car tyre rubber components identified in the samples tested.

The success of the field trial on the B194 and rheological results of the recovered binder confirms the feasibility of the new protocol using the FCL high pressure water retexturing process to recover samples from aged stone mastic asphalt surfacing. Specifically, the protocol was able to provide sufficient quantities of recovered binder for further laboratory assessment.

2.4 RAF Wittering Taxiway

The trial was carried out on the 20 December 2012 in the presence of Mr Craig Coley (DIO), Mr Martin Heslop (Acland), Mr Andre Easey (FCL), Mr Timothy Crisp (FCL), Mr Ashley Starling (FCL) and Mr Daru Widyatmoko (URS). The weather was wet and cold (5^{o}C).

Samples from three trial areas (presented in Figure 4) at RAF Wittering Taxiway were collected, as described below:

- **Section 1**: Control Area (Ch 0 – 100) comprising 100m length with 50m length tested; 21.7Kg material was recovered;
- **Section 2**: Area Treated with emulsion based rejuvenator at 320g/m^2 (Ch 174 – 240) comprising 50m length fully tested; 11.4Kg material was recovered;
- **Section 3**: Area Treated with emulsion based rejuvenator at 360g/m^2 (Ch 250 – 354) comprising 100m length fully tested; 23.2 Kg material was recovered.

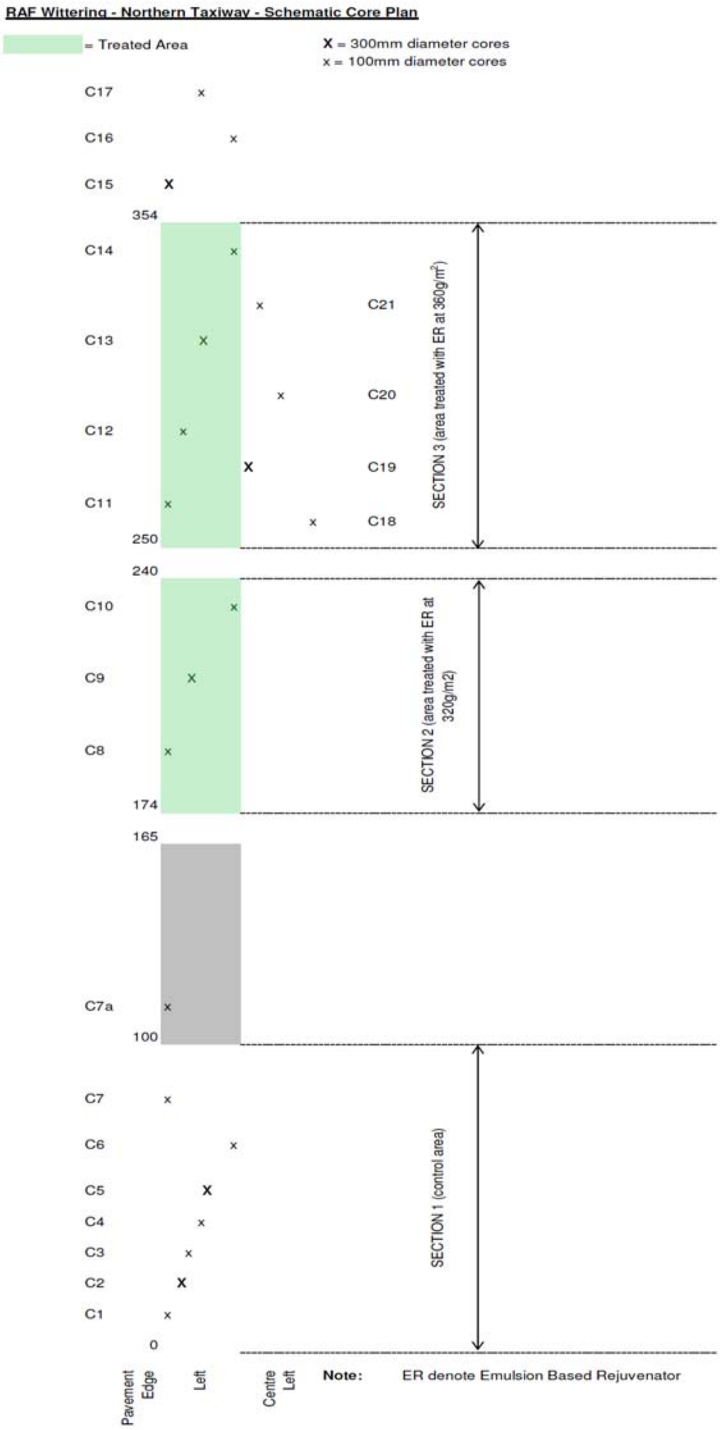

Figure 4: RAF Wittering Taxiway – Schematic Layout of Trial Sections

The sampling work was carried out using Foster Contracting Limited's "Merlin" water blasting machine, which combines high-pressure water at variable pressures up to 2,500 bar, with immediate suction recovery. The surface condition of all three sections was good prior to treatment. However, after treatment, Section 3 had a greater change in appearance. Figures 5 and 6 illustrate the surface condition before and after the sample recovery process.

Figure 5: Control Section 1 - Distinctive Change

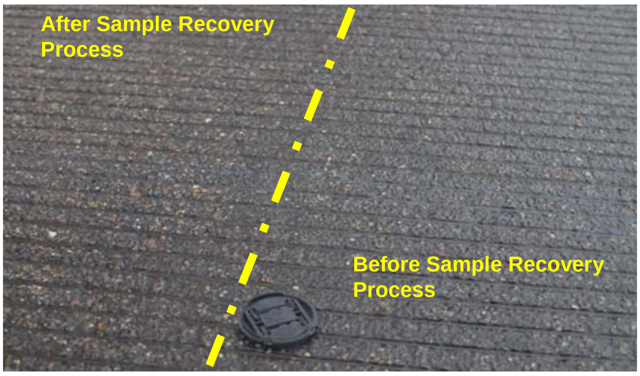

Figure 6: Treated Section 2 – Less Distinctive Change

The following suite of laboratory testing was carried out for the recovered material:

- Composition analysis to BS EN 12697-1 & 2 [6],[7];
- Recovery of binder to BS EN 12697-3 [1];
- Rheology by Dynamic Shear Rheometer (DSR), broadly to BS EN 14770 [2];
- Needle penetration at 25°C to BS EN 1426 [3];
- Saturates, Aromatics, Resins and Asphaltenes (SARA) Analysis using Iatroscan Thin Layer Chromatography with Flame Ionization Detection (TLC-FID).

Composition analysis (mineral aggregate grading and soluble binder content) was carried out for all the recovered loose asphalt samples. A summary of the test results is shown in Table 1 and Figure 7.

Table 1: Composition Analysis Data

Sieve Size (mm)	% Passing		
	Section 1	Section 2	Section 3
31.5	100	100	100
20	100	100	100
14	100	100	100
10	100	100	100
6.3	99	100	100
2	92	91	92
1	74	73	76
0.5	53	54	54
0.125	16	14	13
0.063	3.9	6.2	5.9
Binder Content (%)	***2.0***	***4.5***	***4.2***

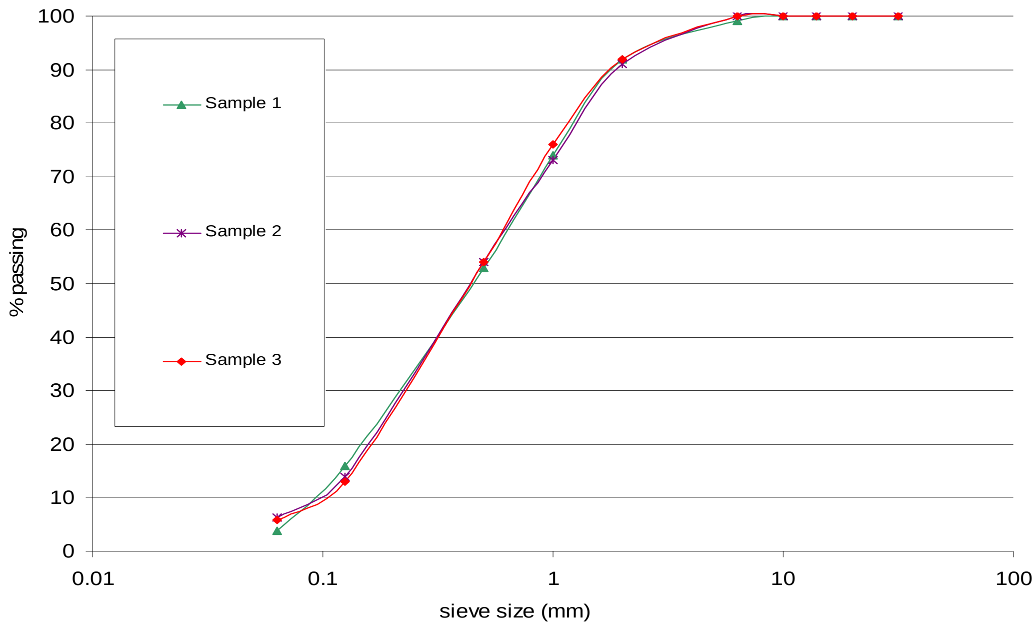

Figure 7: Composition Analysis

The recovered aggregate gradings for the three samples tested were found comparable. The binder contents for the samples recovered from Sections 2 and 3 (treated with emulsion based rejuvenator) were also comparable and higher than that reported for the sample extracted from Section 1 (Control).

Bituminous binders were recovered from the site samples for rheology and needle penetration tests. Composition analysis and binder recovery were carried out by Lincs Laboratory. However, although heated up to 200^{o}C for up to 120 minutes, melting, homogenisation and moulding procedures were not possible as the recovered binders remained in a solid state.

To confirm the above findings, a second binder recovery exercise was carried out and a different third party laboratory was engaged (Chatfield Applied Research Laboratories Ltd). The feedback from the recovery process stated that the binders “foamed with lots of retained air bubbles”, rather unusual behaviour during recovery. Although heated up to 200^{o}C for up to 120 minutes, the recovered binders were still too hard (no signs of binder softening) therefore melting, homogenisation and moulding stages were not possible.

Sub-samples of the recovered binders were also subjected to SARA analysis by using the TLC-FID method. A summary of the SARA analysis report is presented in Table 2. The TLC-FID method allows separation of class components into the following fractions to provide a bulk composition of the material tested:

- Saturates – aliphatic compounds;
- Aromatics – mono-aromatics and polycyclic aromatics;
- Resins – heterocyclic compounds such as acids, bases, phenolics, naturally occurring compounds;
- Asphaltenes – high molecular weight complex matrix.

Table 2: SARA Analysis Data

SARA	Section 1	Section 2	Section 3	The Shell Bitumen Handbook [8], Table 3.1*
Saturates (Aliphatics), %	5.77	4.54	4.66	9.6
Aromatics, %	<0.01	<0.01	<0.01	62.4
Resins (heterocyclics), %	50.57	49.92	42.25	19.8
Asphaltenes, %	43.66	45.54	53.09	5.7

Note: *typical for 100pen grade bitumen; typical range for bituminous binders: saturates 5% – 20%; aromatics 40% - 65%.

Table 2 data suggest that the recovered binders comprised very low aromatics contents and very high contents of resins and asphaltenes when compared with the data reported in [8] for bituminous binders. These findings may partly explain the lack of thermoplastic behaviour of the recovered binders as shown by the difficulty in melting the binders. These unexpected results, perhaps caused by the binder recovery process, need further investigation and ideas to analyse the binder from preservative treated Marshall Asphalt samples are being considered.

3 SUB-TASK 2: PERFORMANCE ASSESSMENTS

3.1 Methodology

Sub-task 2 investigated the effectiveness of asphalt preservatives considering some key performance parameters of untreated and treated surface course naturally aged asphalt materials. The treatment application, carried out in the laboratory to replicate the thickness obtained from a typical application rate, is described in Section 3.2.

The following tests were carried out on the asphalt samples:

- Permeability of treated and untreated porous asphalt cores assessed by using a laboratory hydraulically conductivity test kit in accordance with BS DD 229 [9].
- Scuffing test (TRL Report 176 Appendix G [10]) considered as a candidate for assessing the fretting susceptibility of the core samples. The test was carried out on the 300mm nominal diameter cores. Texture depth to BS 598-105 [11] was also measured before and after scuffing.
- The resistance to age and moisture was assessed by using a modified SATS (Saturation Ageing Tensile Stiffness) testing [12], to the Specification for Highway Works (MCHW1) Clause 953 [13] and BS EN 12697-45 [14] but incorporating lower pressure (0.5MPa) and shorter test duration (24 hours). This test was carried out on surface course samples in untreated and treated condition (as removed from site) and laboratory treated condition respectively. The test involved assessment of Indirect Tensile Stiffness Modulus, ITSM, (BS EN 12697-26 [15]) and tensile strength (BS EN 12697-23 [16]) of the materials before and after the SATS conditioning regime.
- Since there is no known freeze-thaw (F-T) testing for a relatively thin composite of preservative material and asphalt layer, a new ad-hoc protocol was developed which was broadly to AASHTO T283 [17]. This protocol involved subjecting the saturated specimen to 16 hours at -18^{o}C, followed by 24 hours at 60^{o}C, and 2 hours at 25^{o}C. The aim is to assess the resistance to thermally induced shrinkage and swelling on samples with and without preservative treatments and the effect to performance. This protocol was carried out on the saturated sample collected at the end of the SATS test. The splitting test (Indirect Tensile Strength, ITST) to BS EN 12697-23 [16] was carried out following the conditioning protocol.
- Bulk density in accordance with BS EN 12697-6 [18], maximum density in accordance with BS EN 12697-5 [19] and calculated air voids in accordance with BS EN 12697-8 [20].
- The risk for contamination due to application of preservative under a prolonged saturation was assessed by Waste Acceptance Criteria (WAC) leachate test. This protocol was carried out on the water used to saturate the specimen during SATS test.
- The properties of the binder recovered from the samples, treated and untreated, was assessed by using the Gemini Advanced Dynamic Shear Rheometer (DSR) to BS EN 14770 [2].

The above suite of assessments, which will be applicable for each set of materials, is illustrated further in Figure 8 and Figure 9.

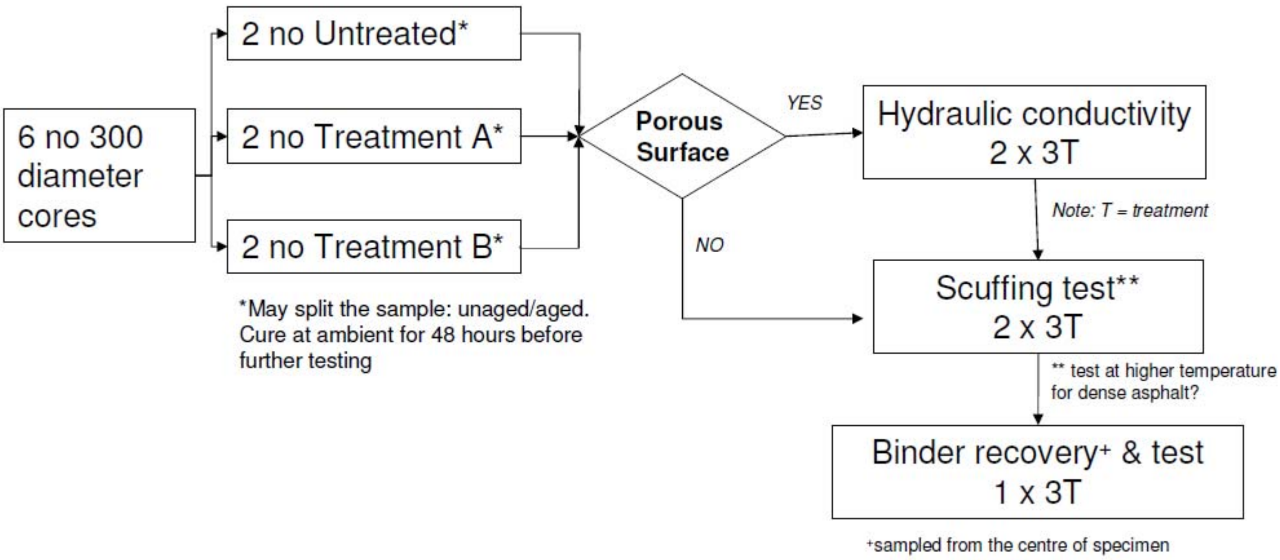

Figure 8: Assessment of 300mm diameter core samples

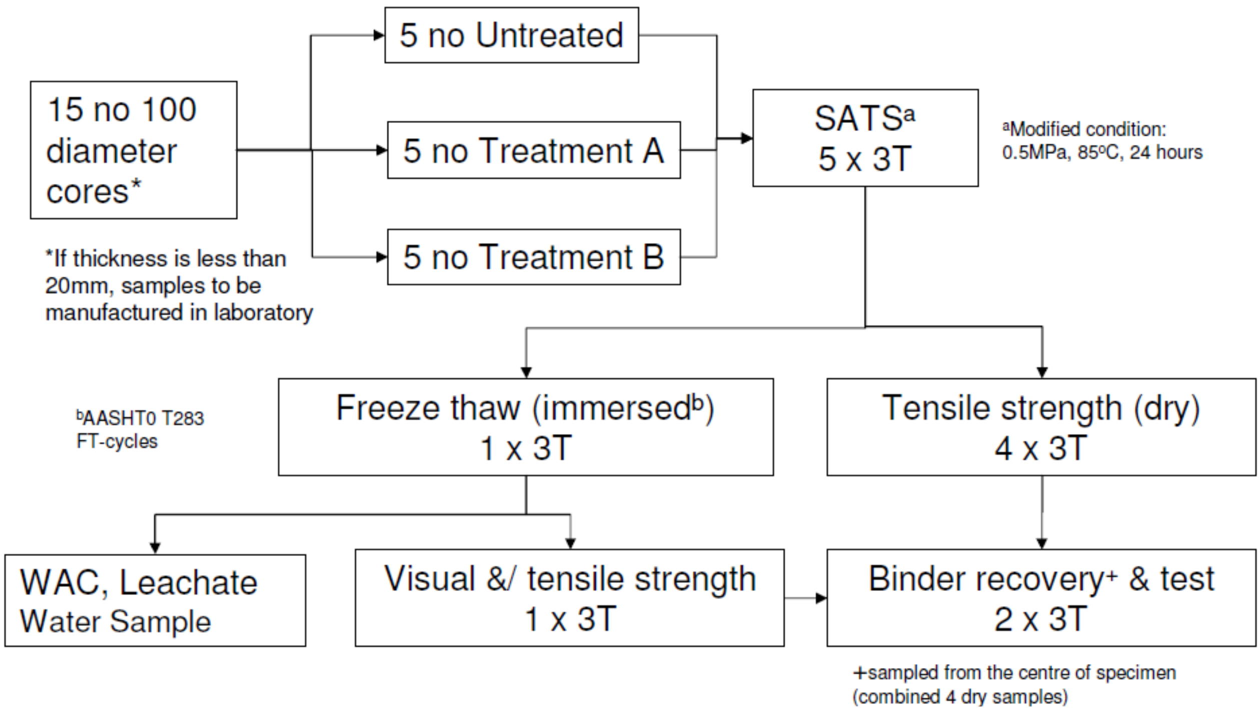

Figure 9: Assessment of 100mm diameter core samples

Note: The protocol presented in Figure 9 is further explained below.

1. Allow the treated samples to cure at ambient for 24 hours in the environmental chamber.
2. Transfer the samples to the modified SATS protocol i.e. 0.5MPa, 85^{o}C, 24 hours. Adopt the full standard reporting requirements i.e. defects, dimension change, saturation and stiffness test.
3. For the SATS immersed sample (wet subset):
   - Carry out freeze – thaw (F-T) cycles in accordance with AASHT0 T283 but without vacuum saturation stage which is not required (because the sample is already saturated). Post F-T: visual assessment (defects, dimension change) and tensile strength, followed by sub-sample from the inner side of the sample for binder recovery and DSR routine testing.
   - Carry out Waste Acceptance Criteria (WAC) test on the water.
4. For the SATS samples above water (dry subset):
   - Carry out tensile strength test;
   - Take sub-sample from the inner side of the sample for binder recovery and DSR routine testing.

3.2 Samples for Testing

Samples were recovered from both road and airfield pavements. Specifically, the following sets of samples were assessed during the current study:

- Cores recovered from M5 Tickenham Hill, typically comprising Thin Asphalt Surfacing (TAS) overlaying existing Asphalt Concrete (AC) or Hot Rolled Asphalt (HRA). TAS was tested in untreated and treated condition (Solvent Type Sealant).

- Cores recovered from RAF Waddington, typically comprising Marshall Asphalt Surface Course (MASC) overlaying existing AC. MASC was tested in untreated and treated condition (Solvent Type Sealant and Emulsion Type Sealant).

- Cores recovered from RAF Wittering, typically comprising grooved Marshall Asphalt Surface Course (MASC) overlaying existing slurry seal and/or Marshall Asphalt (MA) layers. MASC was tested in untreated and treated condition. The latter comprised both samples previously treated on site and also in laboratory (Emulsion Type Rejuvenator).

- Cores recovered from M5 Junction 13-23, typically comprising Thin Asphalt Surfacing (TAS) overlaying existing AC or HRA. TAS was tested in treated condition only (Solvent Type Sealant, Emulsion Type Sealant and Emulsion Type Rejuvenator).

- Cores recovered from RAF Wyton, typically comprising Porous Asphalt Course (PFC) overlaying existing AC. PFC was tested in untreated and treated condition (Solvent Type Sealant and Emulsion Type Rejuvenator).

Note:

Typically, Sealants preserve and protect from further deterioration, whilst Rejuvenators act as sealants, but incorporating rejuvenating agent.

The preservative application (treatment) was carried out in the laboratory and the protocol is briefly described below:

- **Solvent Type Sealant** (hereafter **SS**) – the spray rate was targeted between 0.45l/m^2 and 0.55l/m^2, in accordance with the supplier's recommendation. The calculated amount of sealant required for the application was between 24.0g and 29.4g. The mid point 26.7g was selected as target application. The treated samples were allowed to cure at ambient in the environmental chamber.

- **Emulsion Type Sealant** (hereafter **ES**) – the spray rate was targeted between 0.25l/m^2 and 0.30l/m^2, in accordance with the supplier's recommendation. The calculated amount of sealant required for the application was between 12.0g and 14.4g. The mid point 13.2g was selected as target application. The treated samples were allowed to cure at ambient in the environmental chamber.

- **Emulsion Type Rejuvenator** (hereafter **ER**) – the application was carried out by the supplier, to retain the process confidentiality.

For the 300mm diameter cores the treatment was applied on the surface only, at the rates stated above. For the 100mm diameter cores the treatment was applied on the surface, side and bottom (fully coated application).

3.3 Analysis and Discussion

3.3.1 Relative Hydraulic Conductivity

The relative hydraulic conductivity test method was developed for testing of permeable road surfacing. A radial-flow falling-head permeameter is used to measure the time taken for 2 litres of water under known head conditions to dissipate through an annular area of the surfacing. The principle of the test is illustrated in Figure 10.

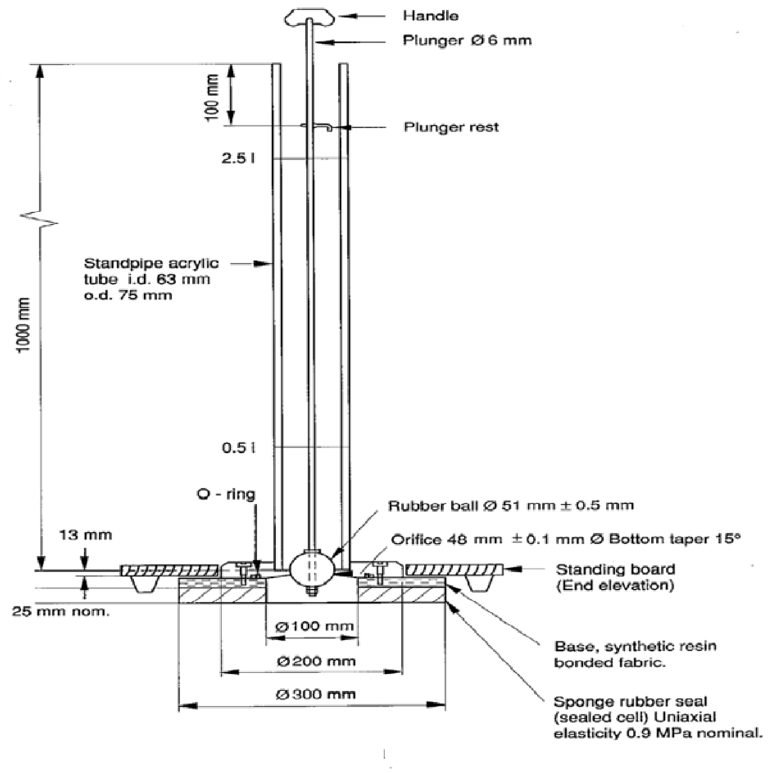

Figure 10: Permeameter Apparatus

Although designed for in-situ testing, this test was attempted on 300mm diameter cores extracted from site, in the laboratory. Unfortunately, due to the standing board overlapping the test specimen, the permeameter could not be secured in place and the rubber annular disc did not provide the required seal. Consequently, no results are available for the relative hydraulic conductivity test under the current study.

3.3.2 Resistance to Combined Effects of Moisture and Ageing (SATS)

The standard Saturation Ageing Tensile Stiffness (SATS) test described in MCHW1 Clause 953 combines the ageing and moisture damage mechanisms in a single laboratory test. The standard parameters for the SATS test are 85^{o}C temperature, 2.1 MPa pressure and 65 h duration. This procedure is considered relatively aggressive and an alternative approach was required in order to widen the applicability of the procedure. The testing parameters were altered to 85^{o}C temperature, 0.5 MPa pressure and 24 h duration (modified SATS). This revised protocol had been found to successfully discriminate the aggregate with a poor track record for moisture sensitivity, with retained stiffness values below 0.6, and good material, with retained stiffness values above 0.6 [21].

During the modified SATS, nominally identical test specimens are subjected to moisture saturation by using a vacuum system. The samples are then transferred into a pressurised vessel partially filled with water, where they are subjected to a conditioning procedure at 85^{o}C temperature, 0.5 MPa pressure and 24 h duration. The top four samples are situated above water, whilst the lower (fifth) sample is fully submerged. The sample arrangement is illustrated in Figure 11. The average stiffness ratio (stiffness after conditioning/stiffness before conditioning) of the individual samples situated above the water is calculated to determine the sensitivity of the material to ageing and moisture.

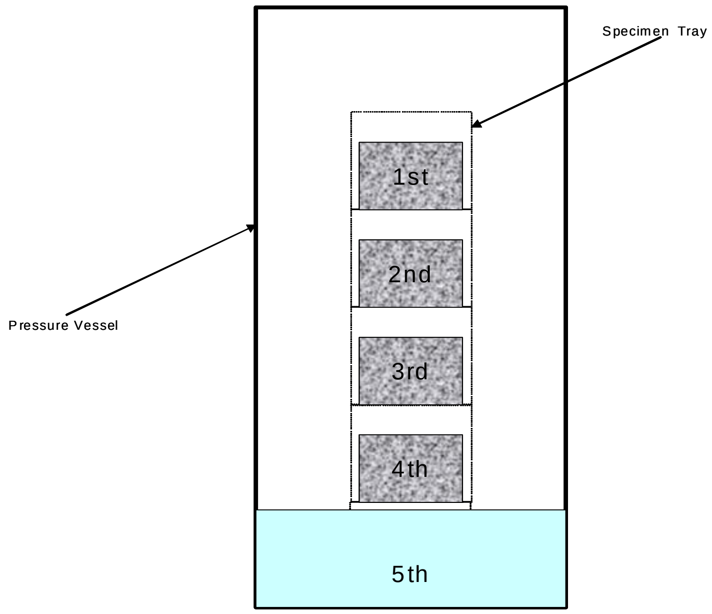

Figure 11: SATS – Sample Arrangement

The modified SATS test data are summarised in Tables 3 to 7 and Figures 12 and 13.

Table 3: Change in stiffness value before and after SATS conditioning – TAS (M5 Tickenham Hill)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Unconditioned Stiffness, $ITSM_U$ (MPa)	Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
		Untreated			
1C (1)	2.300	7.3	5100	2800	0.55
3F (2)	2.366	4.6	3100	2200	0.71
5D (3)	2.336	5.8	3600	2000	0.56
Dummy (4)	n/a	n/a	n/a	n/a	n/a
Dummy (5)	n/a	n/a	n/a	n/a	n/a
Average (1-3**)	***2.334***	***5.9***	***3930***	***2330***	***0.61***
		Treated (SS)			
1A (1)	2.328	6.1	4400	4600	1.05
1B (2)	2.324	6.3	4400	3600	0.82
1F (3)	2.322	6.4	3700	2300	0.62
2E (4)	2.228	10.2	4300	2100	0.49
4F (5)	2.265	8.7	4700	***	***
Average (1-4**)	***2.301***	***7.2***	***4200***	***3150***	***0.74***

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.

** Average values for samples located in positions (1) to (4) [(1) to (3) for Untreated set].

*** Sample was intact following SATS conditioning but was not tested for ITSM (subjected to freeze-thaw, please refer to ITST data presented in Section 3.3.2).

^BS EN 12697-6 Procedure C.

Table 4: Change in stiffness value before and after SATS conditioning – MASC (RAF Waddington)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Unconditioned Stiffness, $ITSM_U$ (MPa)	Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
		Untreated			
19 (1)	2.360	2.6	3400	1800	0.53
43 (2)	2.363	2.5	2700	1000	0.37
66 (3)	2.326	4.0	3000	1000	0.33
69 (4)	2.369	2.3	3200	2200	0.69
68 (5)	2.367	2.4	2700	1100	0.41
Average (1-4**)	***2.354***	***2.9***	***3075***	***1500***	***0.48***
		Treated (SS)			
21 (1)	2.359	2.7	3800	2400	0.63
56 (2)	2.341	3.4	4300	2800	0.65
67 (3)	2.312	4.6	4800	2900	0.60
79 (4)	2.357	2.7	4000	2600	0.65
81 (5)	2.356	2.8	5000	5300	1.06
Average (1-4**)	***2.342***	***3.4***	***4225***	***2675***	***0.63***
		Treated (ES)			
26 (1)	2.355	2.8	8800	4100	0.47
40 (2)	2.374	2.1	6500	2400	0.37
44 (3)	2.329	3.9	6600	2100	0.32
80 (4)	2.320	4.3	6600	3000	0.45
82 (5)	2.334	3.7	5200	4100	0.79
Average (1-4**)	***2.344***	***3.3***	***7125***	***2900***	***0.40***

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.

** Average values for samples located in positions (1) to (4).

^BS EN 12697-6 Procedure C.

Table 5: Change in stiffness value before and after SATS conditioning – MASC (RAF Wittering)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Unconditioned Stiffness, $ITSM_U$ (MPa)	Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
		Untreated			
1 (1)	2.346	6.8	8600	6000	0.70
3 (2)	2.402	4.5	5900	4600	0.78
4 (3)	2.409	4.3	4800	3400	0.71
6 (4)	2.408	4.3	6700	4300	0.64
7 (5)	2.372	5.7	6700	6200	0.93
Average (1-4**)	***2.391***	***5.0***	***6500***	***4575***	***0.71***
		Treated[t] (ER)			
8[t] (1)	2.420	3.8	7800	7500	0.96
10[t] (2)	2.385	5.2	8200	5900	0.72
11[t] (3)	2.380	5.4	9100	6500	0.71
12[t] (4)	2.386	5.1	6700	5300	0.79
14[t] (5)	2.404	4.5	8000	6700	0.84
Average (1-4**)	***2.393***	***4.9***	***7950***	***6300***	***0.80***
		Treated (ER)			
16 (1)	2.413	4.1	5700	6400	1.12
17 (2)	2.440	3.0	4800	4900	1.02
18 (3)	2.402	4.5	8800	6900	0.78
20 (4)	2.413	4.1	6900	5700	0.83
21 (5)	2.425	3.6	6100	5500	0.90
Average (1-4**)	***2.417***	***3.9***	***6550***	***5975***	***0.94***

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.

** Average values for samples located in positions (1) to (4).
^BS EN 12697-6 Procedure C for Untreated samples; BS EN 12697-6 Procedure B for Treated (ER) samples, due to the rejuvenator's adhesiveness.
[t]indicates samples previously treated on site (ER).

Table 6: Change in stiffness value before and after SATS conditioning – TAS (M5 Jct 13-23)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Unconditioned Stiffness, $ITSM_U$ (MPa)	Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
		Treated (SS)			
6 (1)	2.359	5.1	2100	2000	0.95
7 (2)	2.274	8.6	2400	900	0.38
8 (3)	2.292	7.8	5900	3700	0.63
9 (4)	2.273	8.6	3700	2700	0.73
10 (5)	2.316	6.9	2000	1200	0.60
Average (1-4**)	***2.299***	***7.5***	***3525***	***2325***	***0.67***
		Treated (ES)			
11 (1)	2.344	5.7	5400	2800	0.52
12 (2)	2.289	8.0	5200	2300	0.44
13 (3)	2.251	9.5	5000	4400	0.88
14 (4)	2.258	9.2	3500	1900	0.54
15 (5)	2.265	8.9	4100	2700	0.66
Average (1-4**)	***2.286***	***8.1***	***4775***	***2850***	***0.60***
		Treated (ER)			
1 (1)	*2.326*	6.4	4600	3500	0.76
2 (2)	*2.348*	5.6	3200	2100	0.66
3 (3)	*2.293*	7.8	2700	2200	0.81
4 (4)	*2.366*	4.9	3300	2500	0.76
5 (5)	*2.269*	8.8	3700	2000	0.54
Average (1-4**)	***2.333***	***6.2***	***3450***	***2575***	***0.75***

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.
** Average values for samples located in positions (1) to (4).
^BS EN 12697-6 Procedure C for Untreated samples; BS EN 12697-6 Procedure B for Treated (ER) samples, due to the rejuvenator's adhesiveness.

Table 7: Change in stiffness value before and after SATS conditioning – PFC (RAF Wyton)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Unconditioned Stiffness, $ITSM_U$ (MPa)	Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
			Untreated		
2 (1)	2.220	11.2	3100	2500	0.81
3 (2)	2.178	12.9	3600	2100	0.58
4 (3)	2.147	14.1	2200	1700	0.77
6 (4)	2.198	12.1	2400	2500	1.04
7 (5)	2.172	13.1	2700	1100	0.41
Average (1-4**)	***2.186***	***12.6***	***2825***	***2200***	***0.80***
			Treated (SS)		
8 (1)	2.185	12.6	2900	2300	0.79
9 (2)	2.151	14.0	2400	2400	1.00
10 (3)	2.192	12.3	3000	2500	0.83
12 (4)	2.211	11.5	3400	2200	0.65
14 (5)	2.240	10.4	2600	1800	0.69
Average (1-4**)	***2.185***	***12.6***	***2925***	***2350***	***0.82***
			Treated (ER)		
15 (1)	2.234	10.6	3300	2200	0.67
17 (2)	2.231	10.8	3600	2700	0.75
18 (3)	2.111	15.6	2600	2200	0.85
20 (4)	2.214	11.4	2800	2800	1.00
21 (5)	2.192	12.3	3200	2000	0.63
Average (1-4**)	***2.198***	***12.1***	***3075***	***2475***	***0.82***

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.

** Average values for samples located in positions (1) to (4).

^BS EN 12697-6 Procedure C for Untreated samples; BS EN 12697-6 Procedure B for Treated (ER) samples, due to the rejuvenator's adhesiveness.

The data presented in Tables 3 to 7 was summarised in Tables 8 and 9 below.

Table 8: SATS – Moisture and Age-Hardening Data Summary (above water level samples)

Surface Course Material / Site	Condition	*Unconditioned Stiffness, $ITSM_U$ (MPa)	*Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
TAS (M5 Tickenham Hill)	Untreated	3930	2330	0.61
	Treated (SS)	4200	3150	0.74
MASC (RAF Waddington)	Untreated	3075	1500	0.48
	Treated (SS)	4225	2675	0.63
	Treated (ES)	7125	2900	0.40
MASC (RAF Wittering)	Untreated	6500	4575	0.71
	Treated (ER)[t]	7950	6300	0.80
	Treated (ER)	6550	5979	0.94
TAS (M5 Jct 13-23)	Treated (SS)	3525	2325	0.67
	Treated (ES)	4775	2850	0.60
	Treated (ER)	3450	2575	0.75
PFC (RAF Wyton)	Untreated	2825	2200	0.80
	Treated (SS)	2925	2350	0.82
	Treated (ER)	3075	2475	0.82

Note: *average of 4 results; [t]indicates samples previously treated on site (ER).

Table 9: SATS – Moisture and Age-Hardening Data Summary (submerged samples)

Surface Course Material / Site	Condition	*Unconditioned Stiffness, $ITSM_U$ (MPa)	*Conditioned Stiffness, $ITSM_C$ (MPa)	Stiffness Ratio, $ITSM_R$
MASC (RAF Waddington)	Untreated	2700	1100	0.41
	Treated (SS)	5000	5300	1.06
	Treated (ES)	5200	4100	0.79
MASC (RAF Wittering)	Untreated	6700	6200	0.93
	Treated (ER)[t]	8000	6700	0.84
	Treated (ER)	6100	5500	0.90
TAS (M5 Jct 13-23)	Treated (SS)	2000	1200	0.60
	Treated (ES)	4100	2700	0.66
	Treated (ER)	3700	2000	0.54
PFC (RAF Wyton)	Untreated	2700	1100	0.41
	Treated (SS)	2600	1800	0.69
	Treated (ER)	3200	2000	0.63

Note: *1 result; no data available for TAS (M5 Tickenham Hill).

The effect of treatment application using the untreated data as baseline is presented in Table 10.

Table 10: SATS – Properties Changes

Surface Course Material / Site	Condition	Stiffness Ratio, $ITSM_R$ (Changes from Untreated)
TAS (M5 Tickenham Hill)	SS, dry	+0.13
MASC (RAF Waddington)	SS, dry	+0.15
	ES, dry	-0.08
	SS, wet	+0.65
	ES, wet	+0.38
MASC (RAF Wittering)	ER^t, dry	+0.09
	ER, dry	+0.23
	ER^t, wet	-0.09
	ER, wet	-0.03
PFC (RAF Wyton)	SS, dry	+0.02
	ER, dry	+0.02
	SS, wet	+0.28
	ER, wet	+0.22

Note: - denote reduction; + denote increase; ^{t}indicates samples previously treated on site (ER).

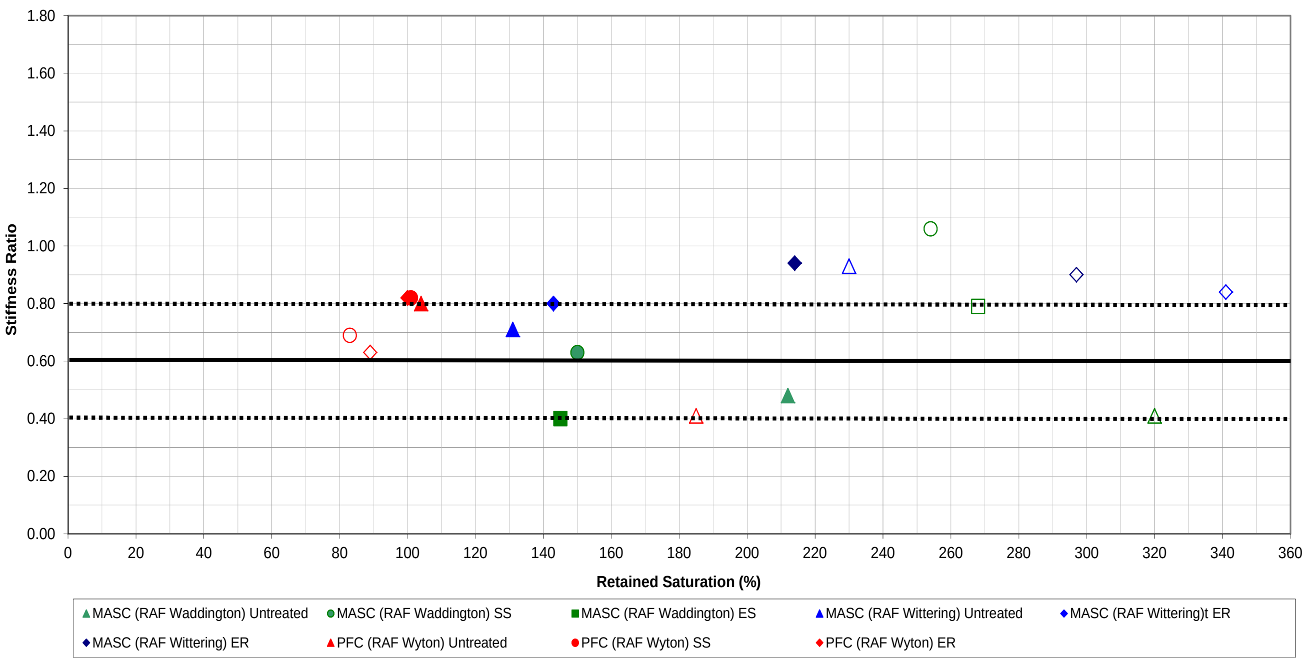

Figure 12: SATS – RAF samples
Above water samples are shown as solid; submerged samples are shown with white centres.

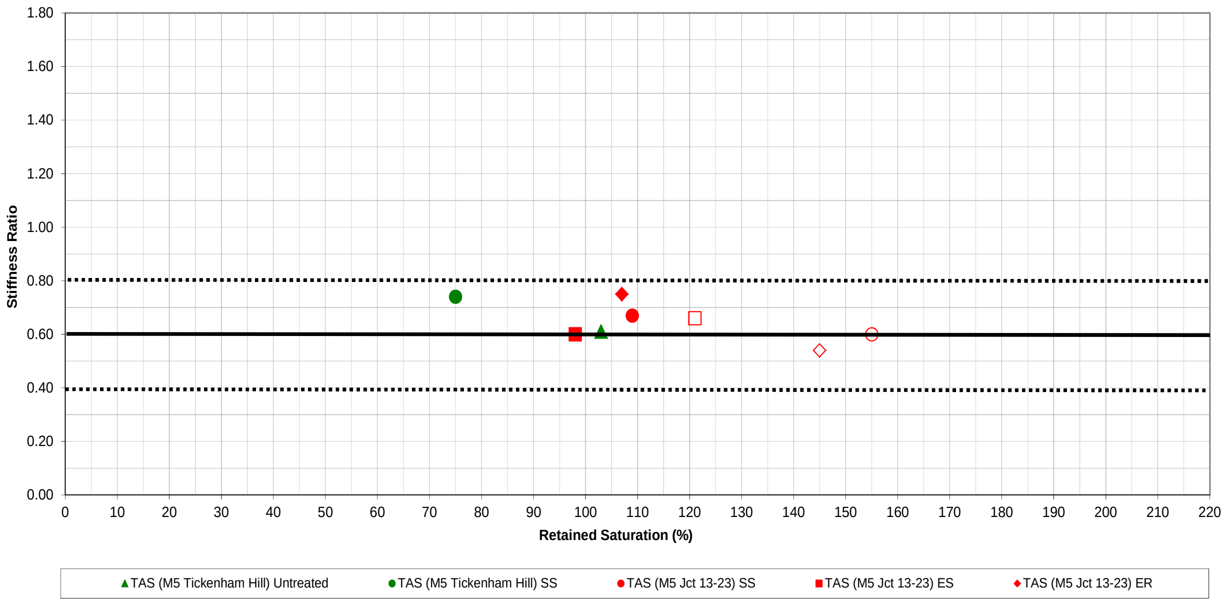

Figure 13: SATS – Roads samples
Above water samples are shown as solid; submerged samples are shown with white centres.
No data available for TAS (M5 Tickenham Hill).

The above data show that the majority of the samples placed above the water level performed satisfactory under the modified SATS conditions, showing retained stiffness values of 0.6 and above. However, MASC (RAF Waddington) both Untreated and Treated (ES) above water samples showed poor performance, having retained stiffness values of 0.48 and 0.40 respectively. The retained saturation levels for the samples above the water varied from 100% to 214% for RAF samples and from 75% to 109% for roads samples.

The retained stiffness values for the submerged samples were found satisfactory (above 0.6), apart from the Untreated samples from RAF Waddington and RAF Wyton. ER treated M5 (Jct 13-23) submerged sample also displayed poor performance, having retained stiffness values of 0.54. The saturation levels were widely spread, ranging from 65% to 341%.

Table 10 data show that the treated specimens (SS and ER in particular) appeared to have stiffness ratios higher than the untreated ones. However, the above water ES treated MASC samples (RAF Waddington) and the submerged ER treated MASC samples (RAF Wittering) displayed poorer performance than the untreated sample.

Overall, for the RAF Waddington samples, the mean stiffness ratios reported in Tables 8 and 9 indicate better performance when compared with those reported in TRL PPR 537 [21].

The visual assessment revealed that no significant changes (i.e. deformation, materials loss, etc) were observed following conditioning, apart from some material loss from the edge of the submerged sample for the RAF Wyton Treated (ER) and the submerged and immediate above water level samples for the RAF Wyton Treated (SS).

The influence of air voids content is shown in Figures 14 and 15.

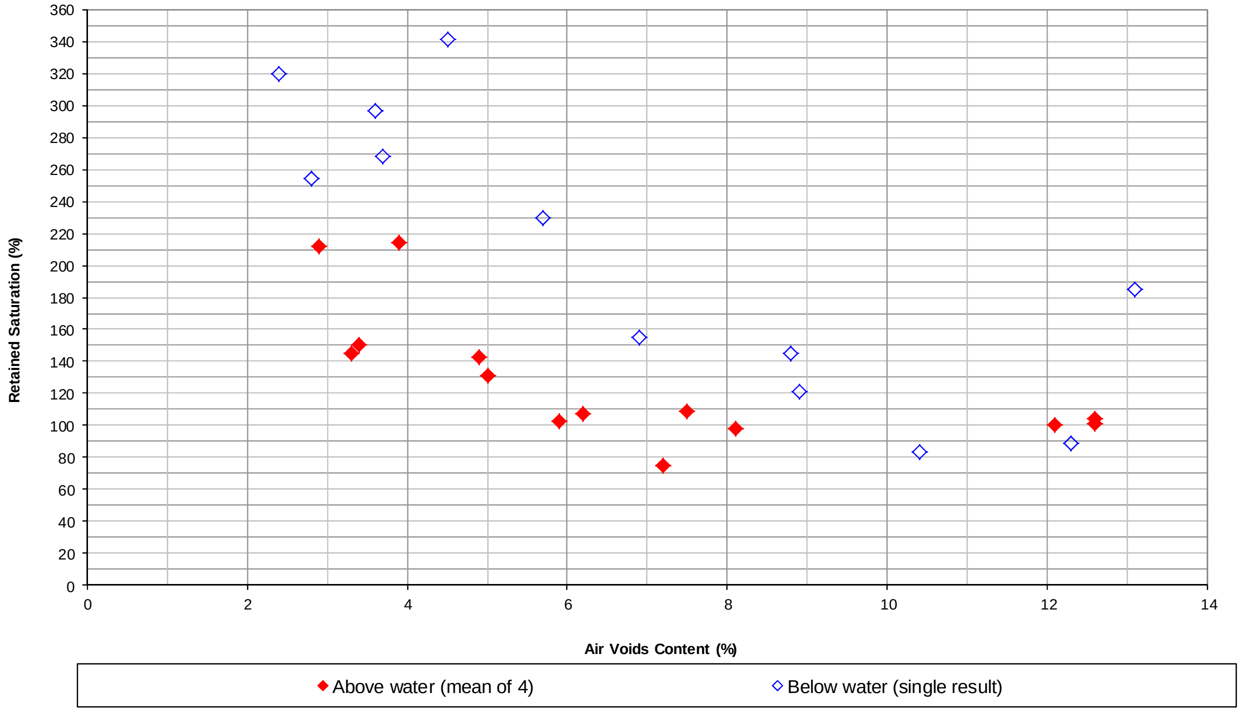

Figure 14: SATS – Retained Saturation (%) vs Air voids Content (%)

The high saturation levels are associated with the low air voids contents, which were reported for most of the samples less than the 8% value, normally adopted in the standard test protocol.

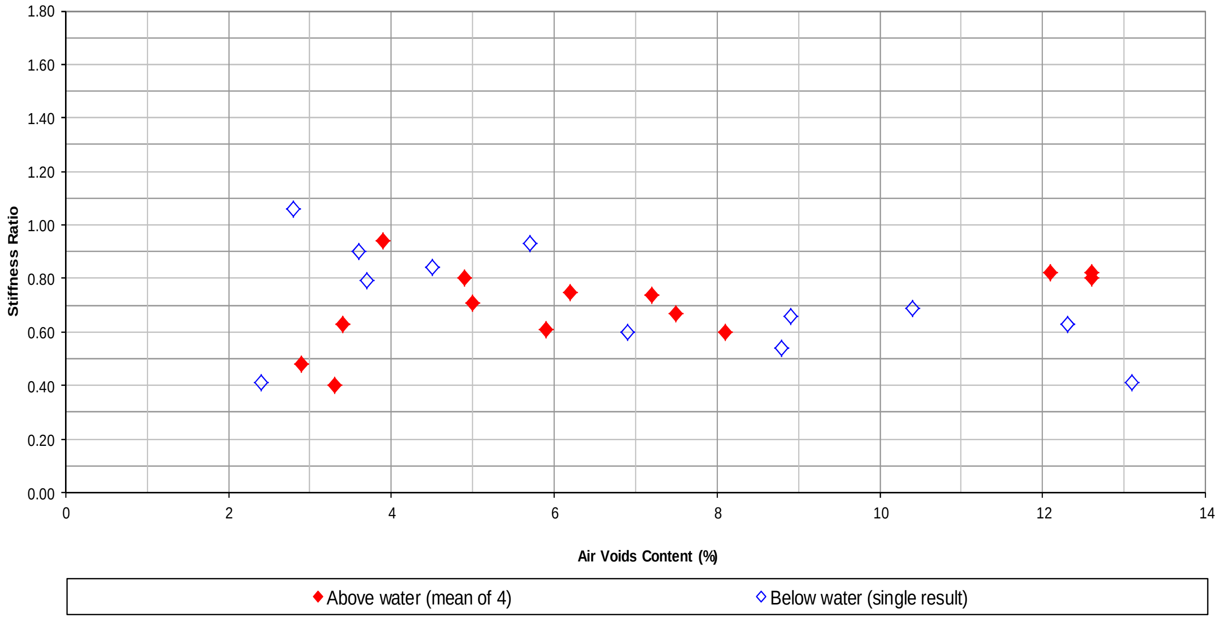

Figure 15: SATS – Stiffness Ratio vs Air voids Content (%)

As shown in Figure 15, there is no apparent relationship between the air voids contents and stiffness ratios. It should be noted, for information only, that the majority of the air voids contents measured for the site samples were below the standard test requirement of 8%±2%.

3.3.3 Indirect Tensile Splitting Test (ITST)

The Indirect Tensile Strength (ITS) Test was carried out as described in Section 3.1. A summary of the ITST results is shown in Tables 11 to 14.

Table 11: Tensile strength after SATS conditioning, Dry (D) and Wet (W) subsets – TAS (M5 Tickenham Hill)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Conditioning Regime	Tensile Strength, TS (kPa)	RITS (%) **
		Untreated			
1C (1)	2.300	7.3	Dry	925	n/a
3F (2)	2.366	4.6	Dry	1010	
5D (3)	2.336	5.8	Dry	893	
		Treated (SS)			
1A (1)	2.328	6.1	Dry	1100	24
1B (2)	2.324	6.3	Dry	1160	
1F (3)	2.322	6.4	Dry	998	
2E (4)	2.228	10.2	Dry	899	
4F (5)	2.265	8.7	Wet	249	

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.
** Ratio between the wet and the average dry subsets.
^BS EN 12697-6 Procedure C.
Wet denote after freeze-thaw cycle.

Table 12: Tensile strength after SATS conditioning, Dry (D) and Wet (W) subsets – MASC (RAF Waddington)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Conditioning Regime	Tensile Strength, TS (kPa)	RITS (%) **
Untreated					
19 (1)	2360	2.6	Dry	689	63
43 (2)	2363	2.5	Dry	568	
66 (3)	2326	4.0	Dry	548	
69 (4)	2369	2.3	Dry	789	
68 (5)	2367	2.4	Wet	411	
Treated (SS)					
21 (1)	2359	2.7	Dry	800	92
56 (2)	2341	3.4	Dry	834	
67 (3)	2312	4.6	Dry	-	
79 (4)	2357	2.7	Dry	830	
81 (5)	2356	2.8	Wet	759	
Treated (ES)					
26 (1)	2355	2.8	Dry	1350	46
40 (2)	2374	2.1	Dry	1090	
44 (3)	2329	3.9	Dry	1300	
80 (4)	2320	4.3	Dry	1060	
82 (5)	2334	3.7	Wet	553	

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.
** Ratio between the wet and the average dry subsets.
^BS EN 12697-6 Procedure C.
Wet denote after freeze-thaw cycle.

Table 13: Tensile strength after SATS conditioning, Dry (D) and Wet (W) subsets – MASC (RAF Wittering)

Sample No (Position*)	Bulk Density^ (Mg/m^3)	Air Voids (%)	Conditioning Regime	Tensile Strength, TS (kPa)	RITS (%) **
Untreated					
1 (1)	2346	6.8	Dry	1860	88
3 (2)	2402	4.5	Dry	1300	
4 (3)	2409	4.3	Dry	981	
6 (4)	2408	4.3	Dry	1320	
7 (5)	2372	5.7	Wet	1200	
Treated (ER)					
8^{t} (1)	2420	3.8	Dry	1460	95
10^{t} (2)	2385	5.2	Dry	767	
11^{t} (3)	2380	5.4	Dry	1450	
12^{t} (4)	2386	5.1	Dry	1400	
14^{t} (5)	2404	4.5	Wet	1210	
Treated (ER)					
16 (1)	2413	4.1	Dry	1550	66
17 (2)	2440	3.0	Dry	1500	
18 (3)	2402	4.5	Dry	1490	
20 (4)	2413	4.1	Dry	1490	
21 (5)	2425	3.6	Wet	1000	

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.
** Ratio between the wet and the average dry subsets.

^BS EN 12697-6 Procedure C for Untreated samples; BS EN 12697-6 Procedure B for Treated (ER) samples, due to the rejuvenator's adhesiveness.
[t]indicates samples previously treated on site (ER).
Wet denote after freeze-thaw cycle.

Table 14: Tensile strength after SATS conditioning, Dry (D) and Wet (W) subsets – TAS (M5 Jct 13-23)

Sample No (Position*)	Bulk Density^ (Mg/m³)	Air Voids (%)	Conditioning Regime	Tensile Strength, TS (kPa)	RITS (%) **
Treated (ER)					
1 (1)	2326	6.4	Dry	796	22
2 (2)	2348	5.6	Dry	640	
3 (3)	2293	7.8	Dry	704	
4 (4)	2366	4.9	Dry	804	
5 (5)	2269	8.8	Wet	160	
Treated (SS)					
6 (1)	2359	5.1	Dry	687	32
7 (2)	2274	8.6	Dry	686	
8 (3)	2292	7.8	Dry	918	
9 (4)	2273	8.6	Dry	927	
10 (5)	2316	6.9	Wet	259	
Treated (ES)					
11 (1)	2344	5.7	Dry	891	91
12 (2)	2289	8.0	Dry	615	
13 (3)	2251	9.5	Dry	905	
14 (4)	2258	9.2	Dry	810	
15 (5)	2265	8.9	Wet	732	

Note: *Position of sample during SATS testing = (1) to (4) denote top to bottom, above water level and (5) denote bottom of the racking, submerged.
** Ratio between the wet and the average dry subsets.
^BS EN 12697-6 Procedure C for Treated samples; BS EN 12697-6 Procedure B for Treated (ER) samples, due to the rejuvenator's adhesiveness.
Wet denote after freeze-thaw cycle.

The data presented in Tables 11 to 14 is summarised in Table 15.

Table 15: ITST Data Summary

Surface Course Material / Site	Condition	*Tensile Strength (Dry) (kPa)	**Tensile Strength (Wet) (kPa)	RITS^ (%)
TAS (M5 Tickenham Hill)	Untreated	943	-	-
	Treated (SS)	1039	249	24
MASC (RAF Waddington)	Untreated	649	411	63
	Treated (SS)	821	759	92
	Treated (ES)	1200	553	46
MASC (RAF Wittering)	Untreated	1365	1200	88
	Treated (ER)[t]	1270	1210	95
	Treated (ER)	1508	1000	66
TAS (M5 Jct 13-23)	Treated (SS)	805	259	32
	Treated (ES)	805	732	91
	Treated (ER)	736	160	22

Note: *average of 4 results; **1 result; [t]indicates samples previously treated on site (ER).
^ The Retained Indirect Tensile Strength (RITS) = $\frac{\text{Conditioned Strength}}{\text{Dry Strength}} \times 100\%$

The effect of treatment application using the untreated data as baseline, where available, is presented in Table 16.

Table 16: ITST – Properties Changes

Surface Course Material / Site	Condition	Wet Tensile Strength*	Dry Tensile Strength**
MASC (RAF Waddington)	SS	+84.7	+26.5
	ES	+34.5	+84.9
MASC (RAF Wittering)	ER[t]	+0.8	-7.0
	ER	-16.7	+10.5
TAS (M5 Tickenham Hill)	SS	n/a	+10.2

Note: **-** denote reduction; + denote increase; [t]indicates samples previously treated on site (ER); *after Freeze-Thaw cycles; **after SATS; n/a denote data not available.

The dry tensile strength values of the TAS (M5 Tickenham Hill), MASC (RAF Wittering) and MASC (RAF Waddington) ES treated samples were considered to be an indication of good residual properties after the SATS conditioning regimes, i.e. tensile strength values generally above 900 kPa. For the TAS (M5 Tickenham Hill) and MASC (RAF Waddington), the dry tensile strengths of the treated specimens appear to be higher than those of the untreated ones. Also TAS (M5 Jct 13-23) SS and ES treated samples showed comparable dry tensile strength values, slightly higher than that reported for the ER treated sample.

Apart from the MASC (RAF Wittering) previously treated on site (ER[t]), all the samples tested showed some increase in dry tensile strength following treatment application, ranging from 10.2% [TAS (M5 Tickenham Hill), SS] to 84.9% [MASC (RAF Waddington), ES]. On the other hand, the wet tensile strength of the MASC (RAF Wittering) ER treated samples showed no improvement, whilst that of the MASC (RAF Waddington) treated samples showed some increase, in particular following the SS application.

Although no significant defects were noticed for the immersed samples, following the freeze thaw cycles, the strength of the

- TAS (M5 Tickenham Hill) - Treated (SS)
- TAS (M5 Jct 13-23) - Treated (SS)
- TAS (M5 Jct 13-23) - Treated (ER)

decreased significantly to values below 400 kPa.

The RITS varied significantly, with some treated samples showing low values, from 22% to 46%.

The failure modes of the samples tested were recorded as combination with none or some broken aggregate.

3.3.4 Waste Acceptance Criteria (WAC)

The water sample collected at the end of the testing (hereafter SATS water) was analysed for WAC leachate testing. The results are summarised in Table 17.

Table 17: WAC Data Summary

	NB. All values are in mg/kg unless otherwise specified							THRESHOLDS			
	Sample Number (Core No)	SATS Water Sample (SS)	SATS Water Sample (SS) Batch B	SATS Water Sample (ES) Batch C	SATS Water Sample (ER)			WAC Inert waste	WAC SNRHW and non-hazardous waste deposited in the same cell	WAC Hazardous waste	Limit of reporting
	Inert waste result	Less than inert WAC									
	SNRHW result		Less than SNRHW WAC	Less than SNRHW WAC							
	Hazardous waste result				Less than hazardous WAC						
	Determinand										
WAC DETERMINED BY LEACHING	Arsenic	0.02	0.01	0.01	0.88			0.5	2	25	<0.1
	Barium	1.2	1.20	0.89	51.0			20	100	300	<1
	Cadmium	0.02	0.02	0.02	0.03			0.04	1	5	<0.02
	Chromium	0.1	0.10	0.10	0.91			0.5	10	70	<0.1
	Copper	1.0	0.90	1.10	4.10			2	50	100	<0.1
	Mercury	0.002	0.002	0.002	0.02			0.01	0.2	2	<0.01
	Molybdenum	0.1	0.10	0.10	3.20			0.5	10	30	<0.1
	Nickel	0.23	0.13	0.15	8.30			0.4	10	40	<0.1
	Lead	0.05	0.05	0.05	0.29			0.5	10	50	<0.1
	Antimony	0.05	0.05	0.05	0.86			0.06	0.7	5	<0.02
	Selenium	0.03	0.17	0.19	0.37			0.1	0.5	7	<0.02
	Zinc	0.2	0.15	0.17	24.0			4	50	200	<1
	Chloride	600	410	400	100			800	15000	25000	<1
	Fluoride	7.5	4.4	5.0	1.8			10	150	500	<3.5
	Sulfate	850	994	816	110			1000	20000	50000	<200
	Phenols	1.0	1.0	1.0	1.0			1			<1
	Dissolved Organic Carbon	270	295	308	160			500	800	1000	<100
	Total Dissolved Solids	3500	3816	3316	570			4000	60000	100000	<2
	Key:	Exceeds Inert WAC			Exceeds SNRHW				Exceeds Hazardous WAC		

Overall, the above data show values lower than the threshold values beyond which there could be risks for contamination to the environment due to the presence of inert and hazardous waste in the SATS water for the SS and ES, although marginally higher results was reported for Selenium.

On the other hand, the data for the ER show values lower than the threshold values for risks for contamination to the environment due to the presence of hazardous waste in the SATS water but mainly higher than the threshold for inert WAC.

3.3.5 Recovered Binder Properties

The rheological properties of the binders recovered from the middle of the samples were determined by using a Gemini Advanced Dynamic Shear Rheometer, in accordance with BS EN 14770 [2]. In this test, the specimen is subjected to repeated shear loading in frequency sweep (frequencies between 0.1 and 10 Hz at 25°C) and temperature sweep (temperatures between 0 and 80°C at 0.4 Hz) modes. The results are summarised in Table 18.

Table 18: Recovered Binder Data Summary

Surface Course Material / Site	**Condition**	**Calculated Penetration (d_{mm})**	**Calculated Softening Point (°C)**	**Complex Modulus G* (Pa) at 0.4Hz & 25°C**
TAS (M5 Tickenham Hill)	SS, dry	24	64.8	1.38×10^6
	SS, dry	22	68.6	1.62×10^6
	SS, wet	31	58.8	8.92×10^5
MASC (RAF Waddington)	Untreated, dry	37	58.4	6.53×10^5
	Untreated, wet	48	59.2	4.07×10^5
	SS, dry	29	61.4	9.83×10^5
	SS, wet	23	69.4	1.48×10^6
	ES, dry	18	61.6	2.40×10^6
	ES, wet	23	64.4	1.54×10^6
MASC (RAF Wittering)	Untreated, dry	37	59.6	6.53×10^5
	Untreated, wet	31	65.0	8.68×10^5
	ER^t, dry	14	70.6	3.60×10^6
	ER^t, dry	16	68.4	2.81×10^6
	ER, dry	20	65.8	2.00×10^6
	ER, dry	18	63.4	2.24×10^6
PFC (RAF Wyton)	Untreated, dry	9	66.6	7.57×10^6
	Untreated, wet	9	65.8	7.76×10^6
	SS, dry	9	74.0	8.61×10^6
	SS, wet	11	72.4	5.71×10^6
	ER, dry	22	61.2	1.62×10^6
	ER, wet	12	71.6	5.10×10^6

Note: ^{t}indicates samples previously treated on site (ER).

The complex modulus (G*) represents the stiffness of the bitumen at a given test condition, and the phase angle indicates the viscoelastic response of bitumen. Lower phase angle denotes bitumen having a predominantly elastic response, whilst higher phase angle denotes bitumen in viscous-liquid condition (note: bitumen is in a pure viscous condition at 90° phase angle). For example, the harder an unmodified bitumen, the higher G* and the lower phase angle will be expected.

The effect of treatment application was assessed for the MASC (RAF Waddington) and PFC (RAF Wyton), using the untreated data as baseline, as presented in Table 19.

Table 19: Binder Properties Changes

Surface Course Material / Site	Condition	Changes from Untreated		
		Calculated Penetration (d_{mm})	**Calculated Softening Point (^{o}C)**	**Complex Modulus G* (Pa) at 0.4Hz & 25^{o}C**
MASC (RAF Waddington)	SS, dry	-8	+3.0	+3.3 x 10^5
	ES, dry	-19	+3.2	+17.5 x 10^5
	SS, wet	-25	+10.2	+10.7 x 10^5
	ES, wet	-25	+5.2	+11.3 x 10^5
MASC (RAF Wittering)	ER^t, dry	-22	+9.9	+29.5 x 10^5
	ER, dry	-18	+5.0	+13.5 x 10^5
PFC (RAF Wyton)	SS, dry	0	+7.4	+10.4 x 10^5
	ER, dry	+13	-5.4	-59.5 x 10^5
	SS, wet	+2	+6.6	-20.5 x 10^5
	ER, wet	+3	+5.8	-26.6 x 10^5

Note: - denote reduction; + denote increase; ^{t}indicates samples previously treated on site (ER).

Viscous to Elastic Transition (VET) temperature represents the temperature at a phase angle value of 45 degrees, at which the elastic component of the complex shear (stiffness) modulus, G', of a bituminous material equates to the viscous component, G", (hence G' = G" at VET). The lower VET temperature, the more viscous the behaviour at low temperature which favours healing.

In addition to VET, the complex modulus at VET (G*@VET) was also found to be a useful parameter to assess any changes in bitumen properties. Plots of VET and G*@VET are presented in Figures 16 and 17.

Based on the available data, Widyatmoko *et al* [22] developed a tentative threshold value for some paving grade bituminous binders after ageing with the scope of minimising the risk of cracking susceptibility of the asphalt mixtures:

- 15pen bitumen: VET<35^{o}C;
- 50pen bitumen: VET<20^{o}C;

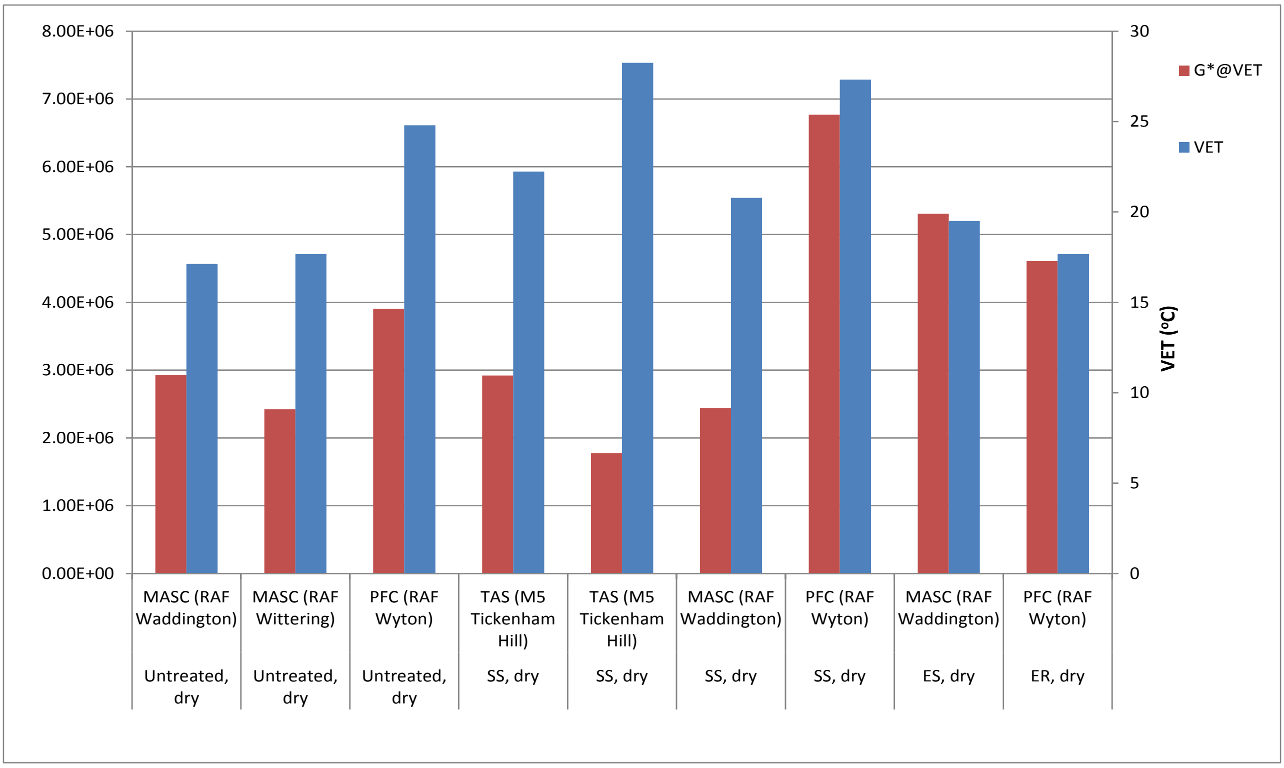

Figure 16: G*@VET and VET – above water samples (SATS)

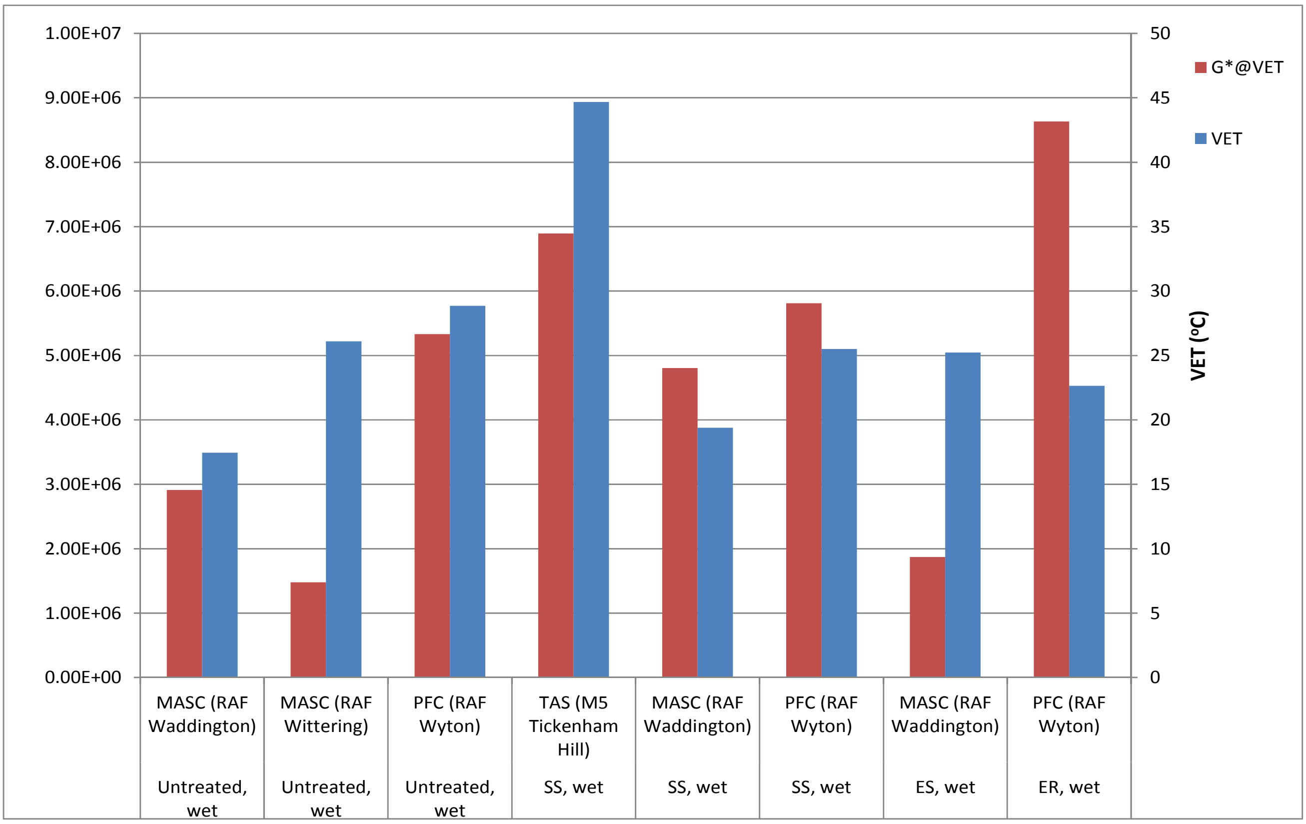

Figure 17: G*@VET and VET – submerged samples (SATS)

The data presented above show:

- MASC (RAF Waddington) treated samples displayed overall a reduction in calculated penetration and increase in calculated softening point and stiffness G* when compared with the Untreated samples data; however, the MASC (RAF Wittering) treated samples although showing the same reduction in calculated penetration and increase in calculated softening point, exhibited some anomalous reduction in stiffness G*. PFC (RAF Wyton) treated samples showed increase in calculated penetration and reduction in stiffness G*. Some anomalous results were found for the calculated penetration and softening point for the PFC (RAF Wyton) wet treated samples.

- Further hardening continued taking place for the MASC treated samples. This may suggest the treatment application did not have positive influence in preserving the bitumen rheology under subsequent ageing.

- PFC (RAF Wyton) Untreated and SS dry treated samples displayed similar recovered binder properties (very low calculated penetration values reported as $9d_{mm}$ and high stiffness G*); however, ER treated sample showed an increase in penetration to $22d_{mm}$. No significant differences in calculated penetration and stiffness G* were reported for the PFC (RAF Wyton) untreated and treated wet samples.

- Caution should be taken for the PFC (RAF Wyton) untreated and SS treated, which showed low penetration values and high stiffness (G*); this may indicate potential for cracking. This may suggest that SS did not have positive influence in preserving the bitumen rheology under subsequent ageing. On the other hand, ER treated samples show higher penetration values and lower stiffness (G*) which suggest the preservative treatment has positive interaction in protecting the residual binder from further hardening.

- MASC (RAF Waddington) dry – SS and ES generated some increase in VET when compared with the untreated sample, confirming the further hardening of the bitumen process reported above; however, the G*@VET for the SS dropped whilst that of the ES increased;

- PFC (RAF Wyton) dry – SS generated some degree of VET and G*@VET increase; however, the ER generated VET decrease and G*@VET slight increase suggesting more viscous behaviour at lower temperatures, hence improved capability for healing.

3.3.6 Texture Depth and Resistance to Lateral Shear Force

The texture depth was determined by the sand patch test in accordance with [11], by measuring the diameter of the circle formed when a known quantity of silica sand to a specified grading is spread evenly over the surface. Texture measurements were carried out on the 300mm diameter cores both before and after the scuffing test.

The scuffing test, carried out broadly in accordance with TRL Report 176 [10] is a simulative high energy test which replicates the turning action of traffic by inducing lateral shear force at the surface. A loaded pneumatic-tyre wheel with its axle set at an angle to the direction of motion was repeatedly passed over the surface of the specimen (500 wheel passes). The scuffing test was carried out at $55^{o}C \pm 1^{o}C$.

The test results are presented in Table 20. Photographs of untreated and treated samples before and after test are presented in Figures 18 to 22.

Table 20: Texture Depth and Resistance to Lateral Shear Force Data Summary

Surface Course Material / Site	Condition	Initial Texture Depth (mm)	Loss in Mass after Scuffing Test (%)	Loss of Texture Depth after Scuffing (%)*
MASC (RAF Wittering)	untreated	1.1	0.17	27
		1.1	0.13	9
		1.0	0.13	20
	ER	1.0	0.03	20
		1.1	0.05	0
		0.9	0.03	22
PFC (RAF Wyton)	untreated	1.6	2.6	168*
		1.5	0.1	6.6
		1.9	0.2	21
	SS	1.7	1.98	n/a
	ER	1.6	0.84**	n/a
		1.5	0.72	n/a

Note: SS and ER application as described in Section 3.2; *sample disintegrated after the scuffing test;** test stopped after 9 minutes as the wheel reached the bottom; n/a denote not available (texture depth after scuffing was not possible due to the damage to the sample).

The initial texture depth measurements for the MASC (RAF Wittering) samples tested were found to be comparable.

The data presented in Table 20 show that the untreated MASC samples displayed slightly higher loss in mass (%) after the scuffing test than that recorded for the ER treated samples.

Overall, the MASC samples tested displayed large variation in the resistance to the scuffing action, ranging from 0% to 27% mass loss.

The PFC (RAF Wyton) samples tested also exhibited comparable initial texture depth and large variation in the mass loss after the scuffing test. The PFC (RAF Wyton) untreated samples exhibited significant variation in the loss of texture depth after the scuffing test whilst the treated samples disintegrated during the test therefore the measurement of the texture depth after scuffing was not possible.

Finally, visual observation of the above intact samples after testing revealed that the action of the scuffing tyre did not show any significant signs of exposed aggregate, by abrasion of the coating bitumen.

Figure 18: MASC (RAF Wittering) Untreated before and after Scuffing Test

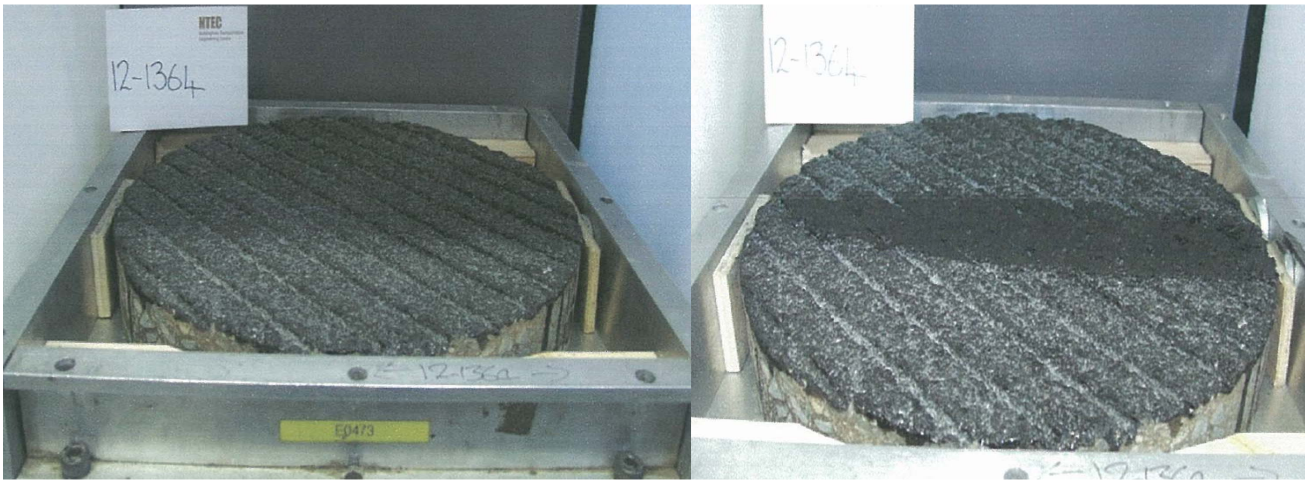

Figure 19: MASC (RAF Wittering) ER treated before and after Scuffing Test

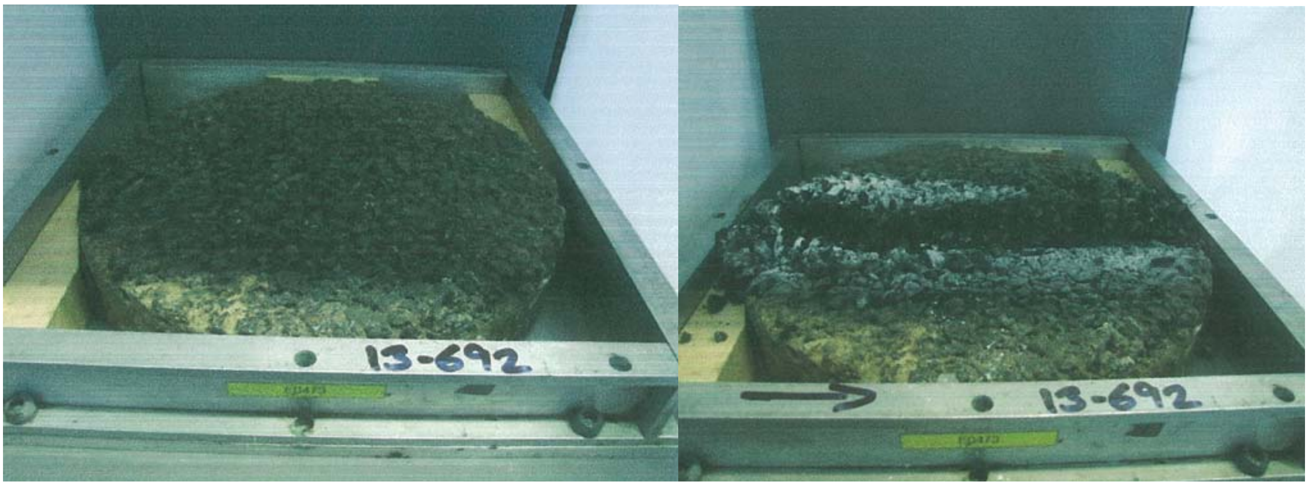

Figure 20: PFC (RAF Wyton) Untreated before and after Scuffing Test

Figure 21: PFC (RAF Wyton) ER treated before and after Scuffing Test

Figure 22: PFC (RAF Wyton) SS treated before and after Scuffing Test

4 CONCLUSIONS

The preliminary findings confirmed the feasibility for using the high pressure water jetting retexturing technique as a means to recover samples from site for further binder assessment. The protocol was further assessed during full scale trials, involving recovering of surfacing sample from untreated and treated sections by using the retexturing process.

Two field trials were carried out for road (B194 Crooked Mile, Essex) and airfield (RAF Wittering) surfacing materials. The recovered binder data for the B194 Crooked Mile SMA material suggested significant hardening.

The second field trial was carried out at RAF Wittering for MASC material, in both treated and untreated condition respectively. The former comprised the use of an emulsion based rejuvenator at two different application rates. The surfacing material was recovered successfully and the composition analysis showed comparable particle size distribution. However, the binder contents for the treated areas were comparable and higher that that reported for the untreated material. The binder recovery process was carried out and the recovered binders were found too hard for melting, homogenisation and moulding preparation stages for further testing. This finding was confirmed by a second laboratory, which also produced very hard recovered binders that could not be tested. SARA analysis revealed some differences in the chemical composition of the recovered binders, with substantially low aromatics and high resins and asphaltenes contents, which are unusual for bituminous binders. This may partly explain the lack of thermoplastic behaviour of the recovered binders. This needs further investigation and the retexturing process may have to be more aggressive in order to obtain asphalt samples from deeper than the estimated 0.5mm to 1mm removal for the leaner and denser materials such as Marshall Asphalt.

The preliminary work during Stage 2 assessment indicated the feasibility for adopting the modified SATS testing as a means to assess the contribution of preservative material against moisture and age. Therefore this protocol was applied for the rest of the materials selected for testing under this project.

The sites and materials selected, treatment application and its effectiveness are summarised in Table 21.

Table 21: Effectiveness of Asphalt Preservative (relative to untreated samples)

	Solvent type sealant (SS)	**Emulsion type sealant (ES)**	**Emulsion type rejuvenator (ER)**
Relative Hydraulic Conductivity	n/a	n/a	n/a
Age & Moisture (SATS)	Better	Same	Better
Freeze Thaw (ITST)	Better	Same*	Same
WAC Leachate	Pass WAC Hazardous Criteria**	Pass WAC Hazardous Criteria**	Pass WAC Hazardous Criteria^
Recovered Binder Properties	Worse^^	Worse	Better
Scuffing	Worse	n/a	Better^^^

Note: n/a denote data not available; *for MASC (RAF Waddington); however, TAS (M5 Jct 13-23) ES samples performed better than the SS treated samples; **marginally higher Selenium reported; ^exceeds Inert WAC but below the Hazardous WAC.
^^Caution –low penetration values for SS treated samples may indicate potential for cracking.
^^^Large variation in retention of macrotexture between individual results for MASC.
No scuffing data is available for the PFC SS and ER treated samples (disintegrated during the test).

5 RECOMMENDATION FOR FUTURE WORK

Further work to establish the high pressure water jetting parameters for each asphalt material type is needed. Sufficient samples are required for binder testing and the protocols for testing need to be robust.

The SATS protocol adopted needs further work to establish precision of the improvements in resistance to ageing and moisture that have been shown, affecting not only the surface, but also the asphalt beneath. The SATS protocol also provides assurance that preservatives do not adversely affect the environment in terms of Waste Acceptance Criteria and should be considered for all future preservative type testing.

In addition to laboratory study, the cost effectiveness of the protocol against the conventional sample recovery methods should also be assessed.

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